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WELDING
AND
ITS APPLICATION

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WELDING AND ITS APPLICATION

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PREFACE

The art of welding has made great progress in the past few years, and today it is one of the most important tools for manufacturing, construction, and maintenance purposes.

The object of this book is (1) to familiarize the beginner with certain fundamental facts concerning the welding process, (2) to give the experienced welding operator a wider understanding of the welding process, and (3) to provide a source of reference for the draftsman, designer, engineer, executive, and anyone else interested in the application of welding. Although emphasis has been placed on electric-arc welding, an attempt has been made to give a picture of the welding industry as a whole.

The author has at times drawn freely from the works of well-known welding organizations, and he wishes to take this opportunity to express his sincere gratitude to all those who so generously cooperated with him in the assembling and preparation of the material. He is especially indebted to the American Welding Society, the International Acetylene Association, Lincoln Electric Company, General Electric Company, Westinghouse Electric and Manufacturing Company, Hobart Brothers Company, Wilson Welder and Metals Co., Air Reduction Sales Company, Linde Air Products, and many other organizations whose names do not appear here. He also feels deeply grateful to the Welding Division of the Delehanty Institute, to his colleagues, to his most valued friend, Frederick R. Weaver, and to his beloved wife, Victoria, for their invaluable assistance.

BONIFACE E. ROSSI.

NEW YORK,
August, 1941.

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WELDING AND ITS APPLICATION

CHAPTER I

WELDING AND ITS ECONOMY

Originally, the economic importance of welding extended mainly to the repairing and the salvaging of all kinds of worn or damaged metal equipment and metal parts. This has been greatly surpassed by the economy brought about by the more recent applications of the cutting and welding processes.

Replacing Castings.—Before the modern processes of cutting and welding developed, many parts of machinery had to be designed as castings, not only because the unit cost of cast iron was comparatively low, but also because the cost of working rolled steel to the desired shapes was so high as to be prohibitive.

Modern cutting and welding processes have made possible the production of complex and intricate shapes at a moderate and reasonable cost, and the unit cost of cast iron has increased considerably. Many products previously made of cast iron are now made of welded steel, at a cost 35 to 60 per cent lower.

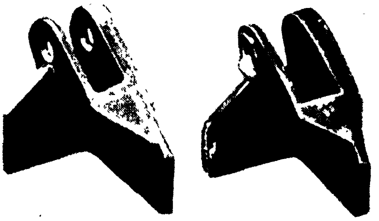


FIG. 1.—Welded structure compared with cast structure. (*Courtesy of The Lincoln Electric Company.*)

Commercial rolled steel has many advantages over cast iron. It costs about one-third as much per pound; it has a unit working strength about six times as great; and its rigidity is $2\frac{1}{2}$ times that of cast iron. The higher unit strength of welded rolled steel, especially in tension, permits a further economy both where weight saving is very important and where weight is of minor importance. The required thicknesses are governed by the kinds of stresses existing. If rigidity is desired, such as in parts carrying weight, as brackets and bases, the steel, built to the same outline dimensions, can be made one-half as thick. If tensile strength is desired, the steel can be designed only one-fourth as thick. If both properties must be present, the steel part should be about one-third as thick as the cast part.

The elimination of patterns is a very important economic factor, for very often the cost of patterns is greater than the total cost of cutting and welding. Also, the manufacturer does not have to provide storage space for the patterns.

Many forms of standard steel shapes are now available. They can be combined to form a great variety of machine parts, and practically any casting may be designed as a welded structure. Also, they afford the opportunity of placing the metal only where strength is needed. Moreover, the manufacturer of machinery needs to carry a smaller inventory, and the scrapping of unchangeable parts is reduced considerably whenever machines are improved or become obsolete.

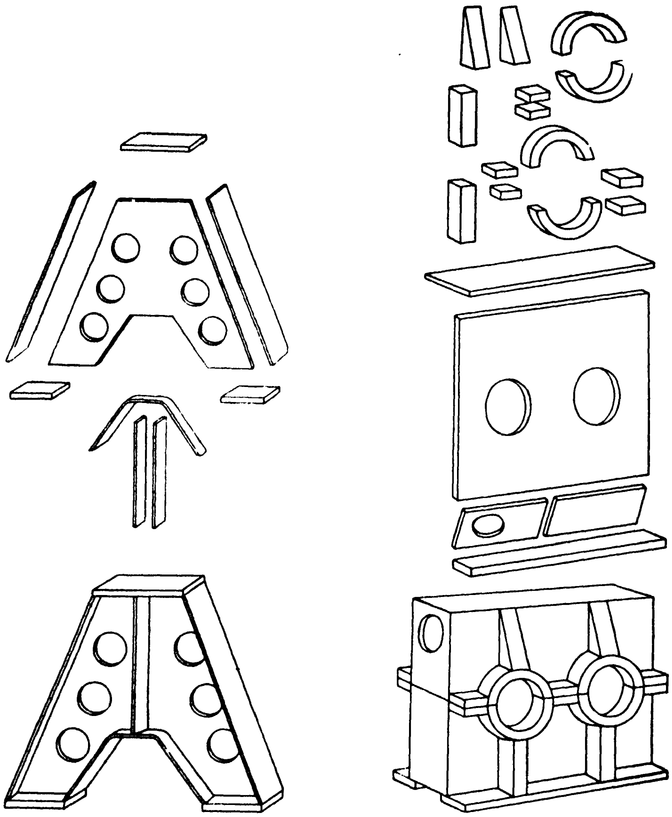


Fig. 2. Fig. 3.

Figs. 2 and 3.—Welded designs using standard rolled-steel shapes.

Often, defects in castings are not apparent until the part in question is machined, and this may mean a possible scrapping after a considerable expenditure of time and money. The chances of the same thing happening with rolled steel are much less, because of the manner in which steel is processed at the mill and the careful inspection it undergoes before shipment.

But the above does not necessarily mean that castings should be excluded from machine construction. In many instances, castings may economically be used. Welding rolled steel to castings, especially to cast steel, or castings to castings, often results in the most economical procedure.

To summarize, welding cuts costs by replacing castings because it eliminates patterns, simplifies assembly, reduces weight, lessens machining, speeds production, reduces loss due to obsolescence, reduces inventory, and thus permits large total savings.

Replacing Riveting.—In the joining of metals, the welding process as a rule produces better results than riveting. In designing a riveted product, the reduction in the net effective section due to the rivet holes must be taken into consideration. This reduction sometimes is as much as 25 per cent, depending upon the size, number, and spacing of the rivet holes. This means that a heavier construction is required.

On the other hand, in welded products the entire cross section of the material is effective since there are no rivet holes. The weight of material is therefore less by as much as 25 per cent, a saving not only in the cost of material but also in the cost of handling being thus effected.

Where a tight job is required, as in pressure vessels, the seams and rivets of riveted products must be calked, but welded seams are tight in themselves.

In the case of steel structures, welding has the following additional advantages over riveting: The connecting material is lighter. The continuity of members is readily obtained, for one can be absolutely fixed to the other. Part of the steel can be shipped directly to the job from the mill. Structural designs not obtainable with riveting can be produced. Joints can be easily made moisture-tight.

Also, it must be borne in mind that the designing of a 100 per cent efficient riveted joint is almost impossible, whereas this degree of perfection can be readily attained in the designing of a welded joint. Furthermore, welding makes possible the use of the modern high-strength steels; but if these were to be riveted, the problem of getting rivets and bolts of the same strength would arise. An additional advantage is that one welding operator often replaces a riveting gang, which is usually made up of four men.

Welding, unlike riveting, is a noiseless process. At the same time, by its use, changes in structures can be made very economically, with a minimum amount of demolition required for alterations. Thus, in the case of business buildings, hospitals, schools, and other structures where these factors are important, profitable activities can be satisfactorily continued during construction.

Another typical application where welding is to be preferred to riveting is in reinforcing certain members of bridges which are in danger of becoming obsolete. Riveting would mean possible removal of existing rivets or drilling of holes for additional rivets. The cost might thus be great enough to warrant scrapping the whole structure. With welding, reinforcements can be welded on without removing rivets, the cost being relatively lower.

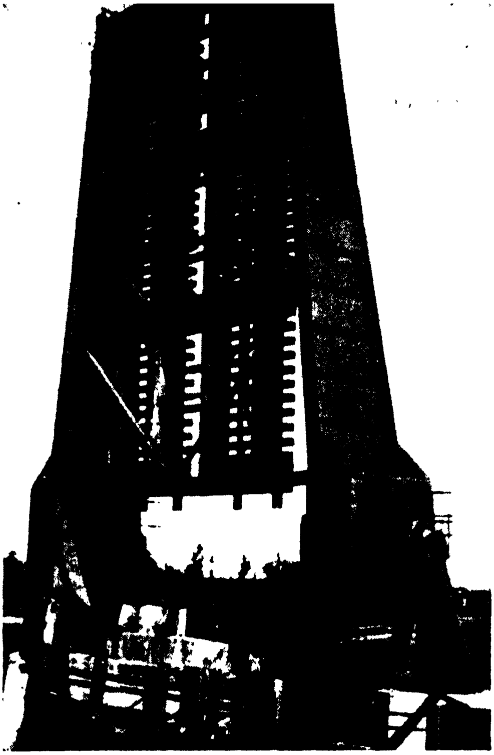


Fig. 4.—Welding replacing riveting (welded bascule span of Florida East Coast Railway bridge, Jupiter, Fla.). (*Courtesy of The Lincoln Electric Company.*)

To summarize, it may be said that welding surpasses riveting because it permits larger total savings, saves weight, simplifies drafting and laying out, and speeds production.

Welding as the Only Means of Fabricating.—Welding is the only solution in cases where the equipment has to be constructed of steel-plate thicknesses greater than those which can be joined by means of riveting and calking. It has thus been directly responsible for the full development of fields formerly restricted by the lack of suitable means of fabricating the necessary equipment. Large cracking stills, used in the refining of petroleum, are an example.

New Materials and Special Welding Processes.—Many special high-strength materials have been developed recently because their use has been ensured by special welding processes. Notable among these are corrosion-resisting steels, such as high-strength stainless steel used in the fabrication of high-speed and light-weight railroad trains.

Appearance and Its Sales Value.—The appearance of fabricated products is of the utmost economic importance, for often it is the determining factor as to whether or not it has any appeal to a prospective buyer.

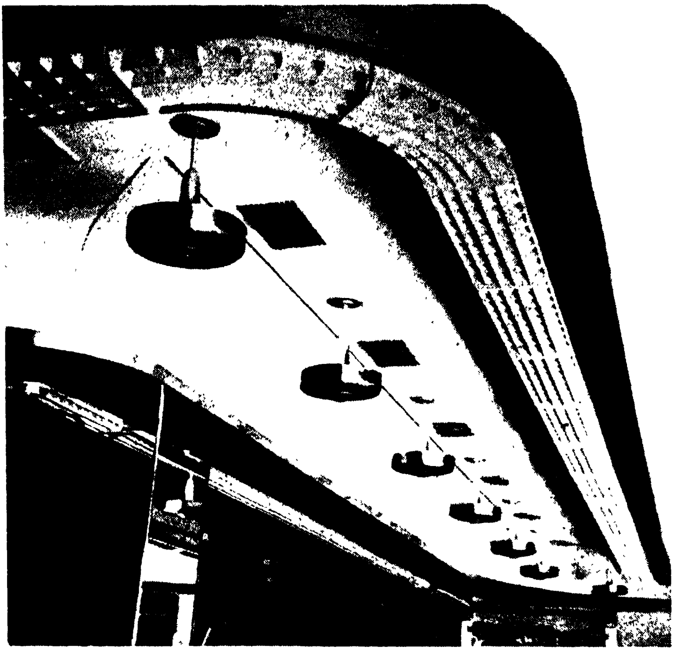


FIG. 5.—Appearance of welded structure and its sales appeal. (*Courtesy of The Linde Air Products Company.*)

When welded products were first introduced, people often reacted against them because they had an unfamiliar appearance. To them, the lack of rivets often meant lack of strength and security, and the lack of flaring contours and sweeping fillets meant lack of beauty.

With time, the welded seam has become a familiar sight, and welding has now come into its own in sales appeal. For example, in the field of light machinery and equipment, such as refrigerators, washing machines, stoves, ironers, and the like, welding has greatly improved their appearance.

Considering Welding.—In determining the most economical and desirable procedure for fabricating, it is important that each case be examined on its own merits. Just because welding has been adopted for certain purposes, it is not necessarily the best process for all purposes. A good cost estimate of each method should be made before deciding on any specific one.

CHAPTER II

PRACTICAL APPLICATIONS OF WELDING IN MANUFACTURING, CONSTRUCTION, AND MAINTENANCE

The economies and improvements brought about by the welding process have stamped it as the outstanding tool for manufacturing, construction, and maintenance purposes. A brief description and illustrations of only a few of the present applications of welding will be given in this chapter, for a discussion of each type of application in industry would require far more space than this chapter affords.

Aircraft Structures.—Welding has been successfully adapted by the aeronautical industry to the construction and maintenance of airplanes, engines, and accessories. The economical use of material to achieve low weight in the structure requires a number of sizes and gauges and consequently a multiplicity of joints. The laboratory- and service-test results have been applied to the design and fabrication of aircraft operating under all conditions. Welding has been used successfully for the largest transports and for the smallest sport airplanes.

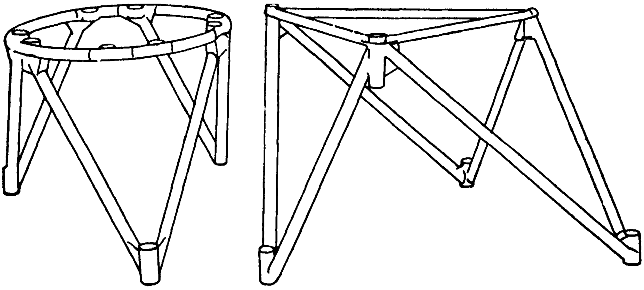


FIG. 6.—Welded motor housings as used in aircraft construction.

The welded joint has the advantage of simplicity, rigidity, and relatively high strength, for no metal is removed for rivet or boltholes. There is no deterioration if it is properly protected against corrosion.

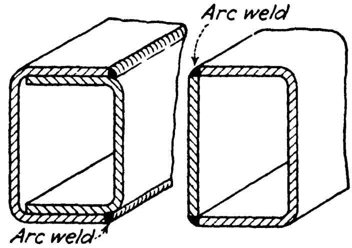
Materials that can be easily welded to obtain a high joint efficiency have been developed and standardized.

To date, the oxyacetylene process is the most flexible type for aircraft work, and it has been found adaptable to the welding of ferrous and nonferrous parts of the lightest and heaviest sections used in airplane construction. It is used for joining the several structural parts of the airplane, such as wings, fuselage, control surfaces, and landing gears, for engine jackets, exhaust manifolds, tanks, and the hard surfacing of tail skids and engine valves.

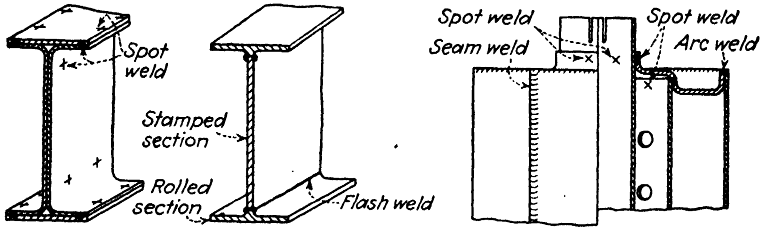
The oxyhydrogen process is used for welding aluminum and the non-heat-treatable aluminum alloys for the manufacture of fuel, oil, and water tanks, fairing, and other miscellaneous low-stressed parts.

Electric-arc welding has been applied principally to the welding of structural parts, such as fuselages, landing chassis, and control surfaces.

Electric-resistance welding has been used to a limited extent in the form of (1) flash welding for butt joints, and (2) spot welding for corrosion-resistant steels and for aluminum and aluminum alloys.



Section of typical frame side member



Section of typical frame X-member

Typical muffler

FIG. 7.—Welding as used in automotive construction.

Automotive Products.—The automotive industry has adopted welding processes ensuring reduced cost of production only after extensive and exacting research. Processes adapted to repetitive operations on a large scale have been developed at great expense to meet exacting requirements.

Some of the automotive parts in the manufacture of which welding plays an important role are rear-axle housings, wire-wheel hubs, disk wheels, connecting rods, mufflers, brake-equalizer shafts, torque tubes, generator housings, and fuel tanks. Resistance welding, electric-arc welding, and gas welding are all used to manufacture one part or another.

Barrels and Drums.—The automatic welding process is generally used to weld containers such as steel beer barrels and metal drums. To withstand the rough handling that such items receive in their service life, the welds must possess high tensile strength and ductility and good resistance to corrosion.

Boilers and Tanks.—Tanks are usually classified according to size and duty. Size is determined solely by capacity requirements, and duty is determined by the operating conditions, such as pressure, temperature, and chemical reaction. The two factors combined regulate the type of tank construction to be employed.

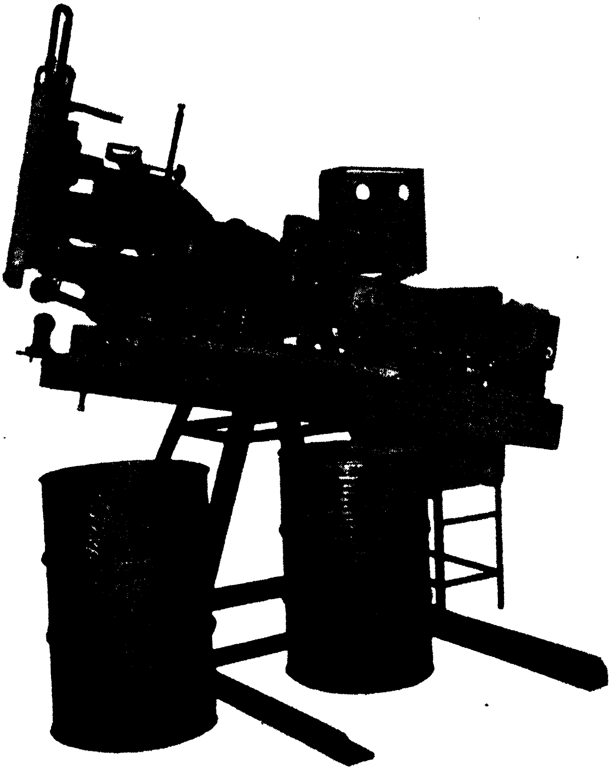


FIG. 8.—Welded steel drums. (*Courtesy of The Lincoln Electric Company.*)

Tanks such as pump tanks, barrels, and domestic-storage and small dispensing tanks may be classified as small tanks if they range up to 100 gal. Storage tanks, septic tanks, vats, pickling tanks, and other types ranging in size from 100 to 3,000 gal. may be called medium tanks. Tanks of over 3,000 gal. capacity are known as large tanks. Among them may be listed bulk-storage tanks, gasholders, and large storage bins and hoppers. Pressure vessels are those vessels which undergo a high superimposed pressure.

In most cases, tanks, both large and small, are ideally suited to welded fabrication. To serve their purpose, the tanks must be leakproof and also sufficiently strong to carry all loads imposed. Welding serves these requirements generally at a lower cost than riveting, for reasons previously outlined.

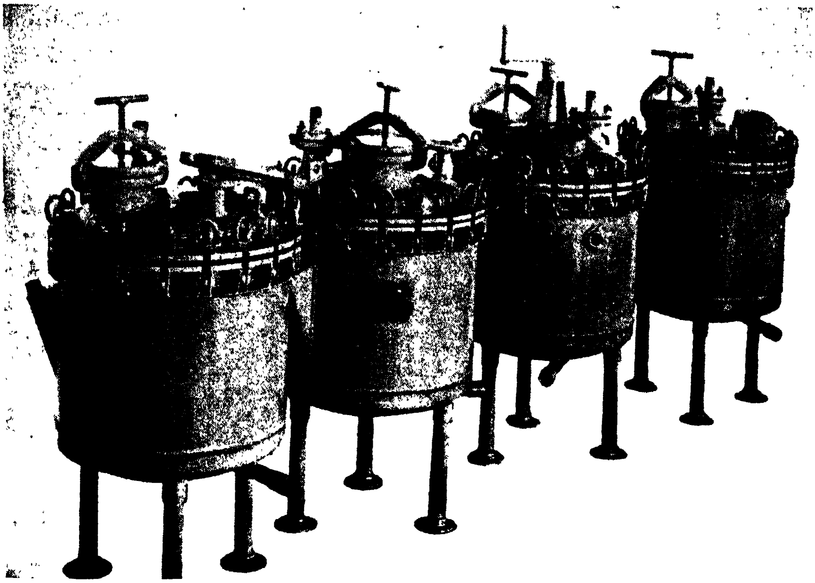


FIG. 9.—Welded jacketed tanks. (*Courtesy of L. O. Koven and Brother, Inc.*)

FIG. 10.—Welded treating tower, 8 ft. diameter by 62 ft. high. (*Courtesy of Treadwell Construction Company.*)

Large storage tanks, such as those used for oil, chemicals, gasoline, or water, are fabricated by hand, but automatic welding may be used to advantage on smaller ones.

Bridges and Piers.—In the last few years, there have been a number of bridges erected entirely of welded construction, but the welding process has been employed extensively in a great number of bridges, especially in European countries.

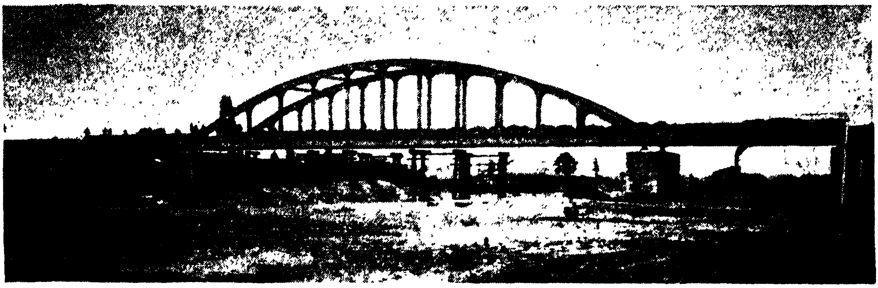


FIG. 11.—A welded 188 ft. Vierendel truss span bridge (Belgium). (*Courtesy of The Lincoln Electric Company.*)

Welded construction eliminates the trouble resulting from nonregister of rivet holes which cannot be predicted accurately.

Hundreds of small girder-type highway bridges have recently been constructed by welding. Suspended beneath the girders are usually two or three floor beams which are welded to the bottom flange of girders at each end. The floor stringers are in turn welded to these beams. In some cases, counties use salvage steel for construction of this type of bridge, and a very economical structure results.

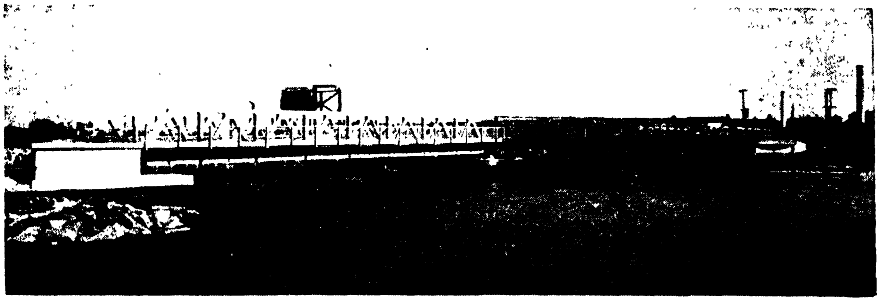


FIG. 12.—Welded highway bridge. (*Courtesy of The Lincoln Electric Company.*)

Widening of highways has often caused the removal of narrow bridges which may be salvaged and reerected by means of welding for use on secondary roads.

There is an increasing use of welded-steel-plate bridge floors. Steel reinforcing for concrete bridge floors is often also welded in place.

Owing to the ability of the welding process to fuse reinforcing members directly to weakened existing members in the most efficient and economical manner, many bridges that had been condemned or had had the load limits greatly reduced because of a corrosion-weakened structure have been placed back in service with the original or greater allowable load limits in force. Welding, combined with the use of the cutting torch for accurate cutting and fitting, lends itself ideally to this application.

The welded fabrication of steelwork for piers effects worth-while economies and, at the same time, provides stronger and stiffer construction. A typical example of this is offered by the all-welded-steel pier extending into the Pacific Ocean for approximately ½ mile from Davenport, Calif.

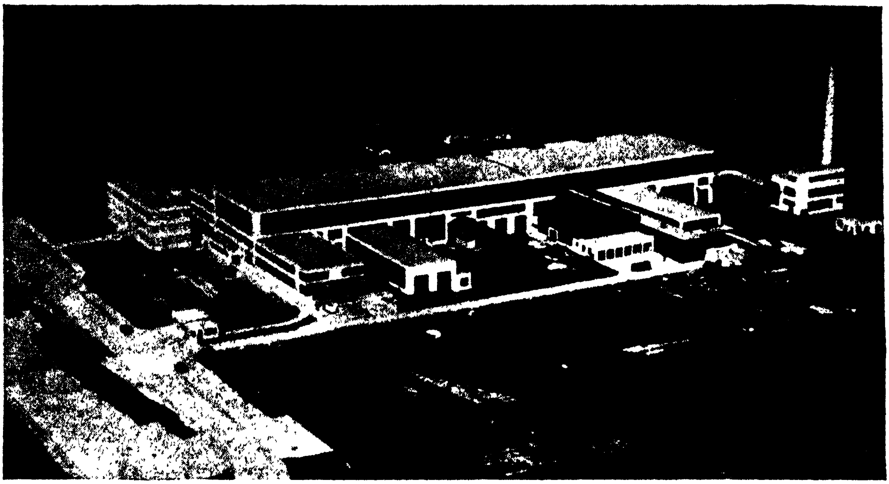


FIG. 13.—Modern manufacturing plant, the steel work of which was entirely welded. (*Courtesy of The Lincoln Electric Company.*)

Building Construction.—The application of welding in building construction has developed rapidly in the past few years. The elimination of noise is one factor that has made its use desirable in localities where this feature is of importance.

The structural frameworks for hundreds of buildings of all sizes and types have been fabricated and erected entirely by the welding process. These structures include office buildings, mill buildings, powerhouses, airplane hangars, dwellings, and packing houses.

There are thousands of structures in which welding has been used extensively either as a shop-fabricating or as a field-erection tool. Typical examples of such applications include field welding of bolted connections; shop-welded fabrication of trusses, column bases, lintels, and other details; and field welding of steel-plate floors, erected bar joists, and metal roofing.

Fig. 14.—Blanking die the cutting edge of which was surfaced by welding. (*Courtesy of The Lincoln Electric Company.*)

Cranes.—Many and varied types of crane are built entirely of arc-welded construction. The advantages of the new construction are greater strength and stiffness per pound of material.

Fig. 15.—Welded dump bucket. (*Courtesy of L. O. Koven and Brother, Inc.*)

Cutting Tools and Dies.—Tools and dies for cutting metal may be made of ordinary steel and provided with a cutting edge comparable with that of high-speed tool steel. This is accomplished by the deposition of a special weld metal on the tip of the tool. The tool or die is then ground to the proper shape for any cutting operation such as turning, planing, milling, or shaping. Tools of high-speed tool steel or ordinary steel hard-surfaced can be refaced in the same manner innumerable times.

Earth-moving Equipment.—Probably no type of material-handling equipment or machinery is subjected to such severe service as power shovels, trenchers, and similar equipment. It is a tribute to welded construction that it has been found most satisfactory for this class of machinery.

Furnaces and Heating Boilers.—Welding is preferred in the fabrication of steel furnaces and heating boilers because it makes possible seamless construction, having the ability to withstand pressure, corrosion, and rapid variation in temperature.

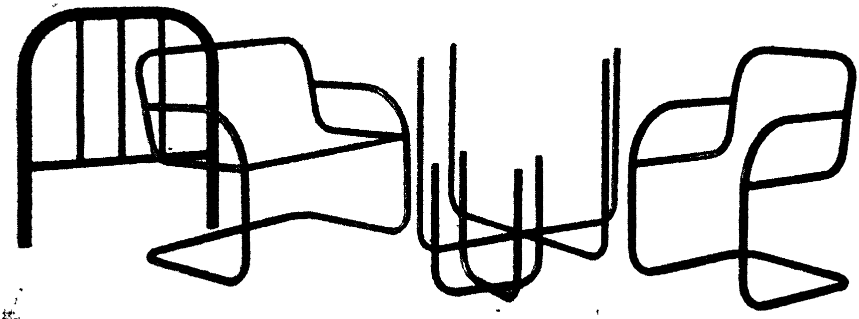


FIG. 16.—Welded metal furniture. (*Courtesy of The Lincoln Electric Company.*)

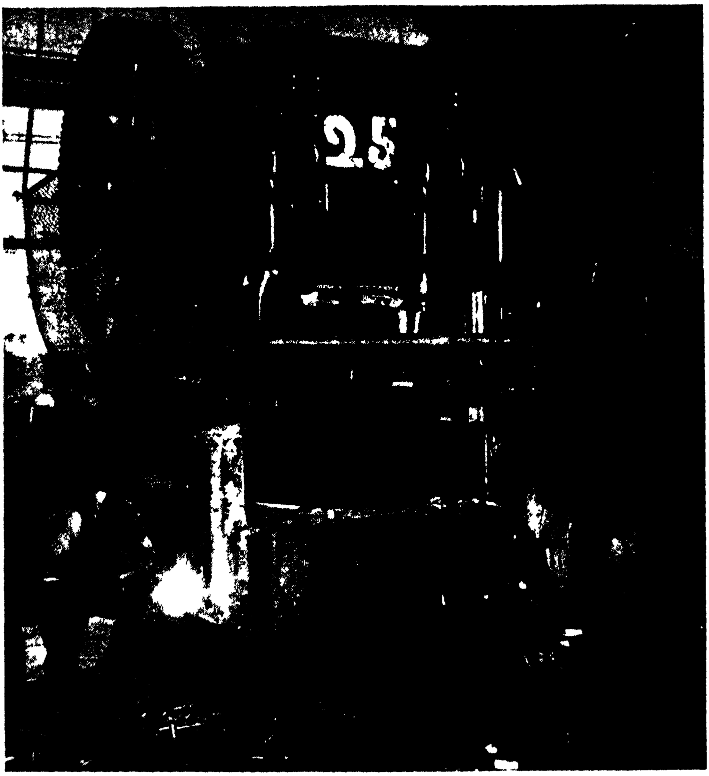


FIG. 17.—Broken leg of cast-iron press repaired by welding. (*Courtesy of The Lincoln Electric Company.*)

Furniture.—Metal furniture is very often fabricated most economically by welding. Tubing is most generally used in the making of bedsteads, chairs, and table frames. Welding eliminates the use of fittings in all connections by fusing one member directly with another, one-piece construction of greater strength and rigidity for least weight being the result.

General Maintenance and Repairs.—Welding is, of course, not confined solely to manufacturing and construction. It is used as a handy and economical tool in repair and reclamation of any parts that might otherwise have been discarded. As a matter of fact, one of the first uses of welding was to repair broken machinery and equipment parts. In its use solely as a repair and general maintenance tool, the welding process saves industry millions of dollars annually.

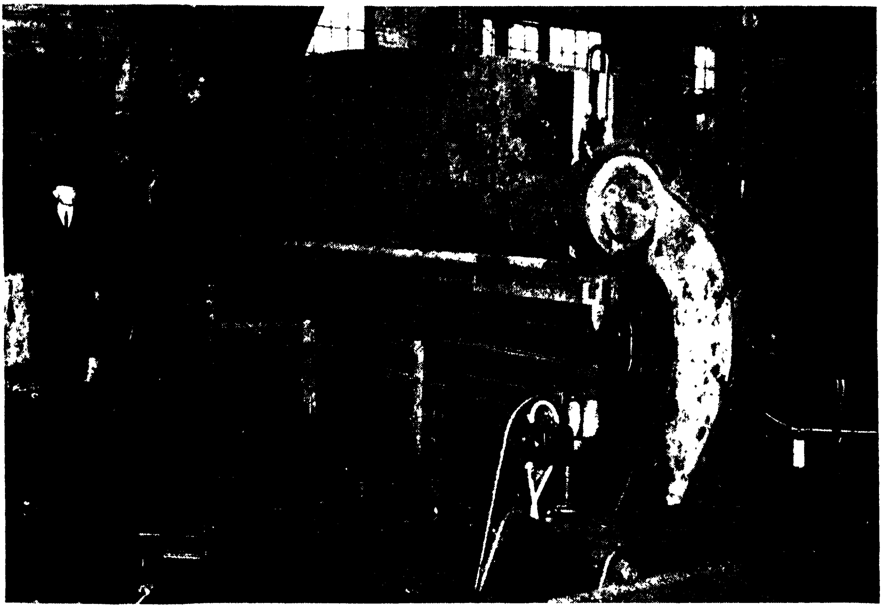


FIG. 18.—Welded 500-ton-capacity steel press brake. (*Courtesy of The Lincoln Electric Company.*)

In general, it may be said that practically any metal part which has become broken or worn in service can be made as good as new by welding.

Machinery and Machine Parts.—Conclusive proof of the reliability of welded construction in machinery fabrication is found in the fact that the type of machinery which is subjected to severe shop loads, such as presses, brakes, punches, and shears, is now being built of welded rolled steel. Welded construction is regarded as practically standard in the manufacture of this type of machinery, for it affords extreme rigidity and strength.

Ornamental Iron.—Skill and artistry, so essential in ornamental ironwork, are aided by the use of the welding process because this process simplifies the uniting together of the component parts of the structure. The maximum strength is also produced by the use of this construction.

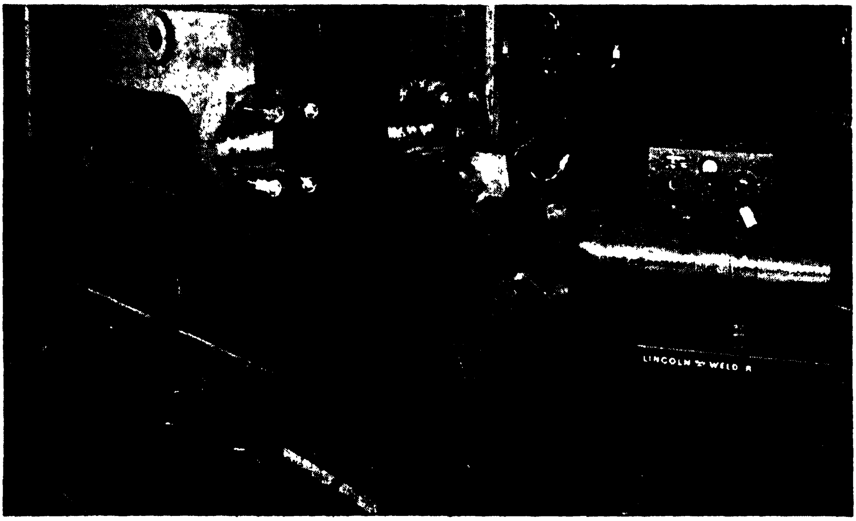


FIG. 19.—Welded 5-ton-press housing. (*Courtesy of The Lincoln Electric Company.*)

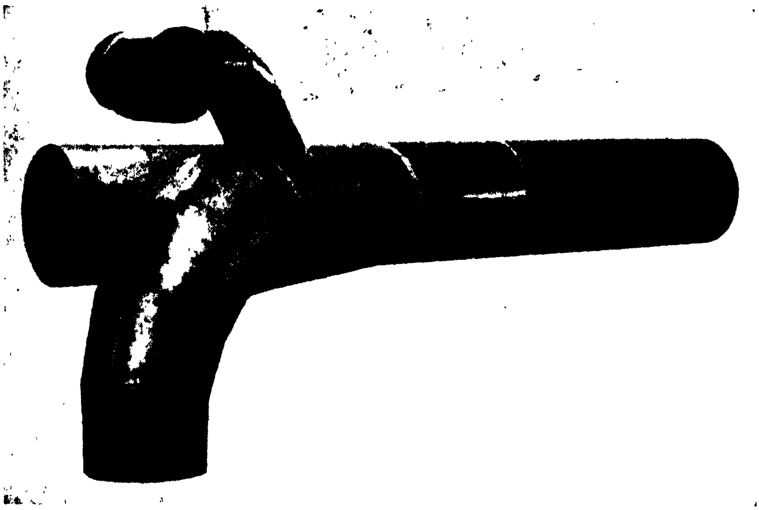


FIG. 20.—Typical welded lightweight pipe. (*Courtesy of L. O. Koven and Brother, Inc.*)

Pipes.—Hundreds of miles of piping systems welded in shop and field have been installed in office buildings, hospitals and schools, industrial plants, powerhouses, and ships.

The advantages of welded piping systems include permanently tight connections of greater strength and rigidity, more pleasing appearance, easier and cheaper application of insulation, simplification of design of fittings, and elimination of many fittings required by mechanically connected systems.

Welding is extensively used in the construction lines for the transmission of oil, gas, water, and many other materials. Many thousands of miles of pipe lines of various types have been fabricated by this process. The sizes of these lines may range from 6 to 84 in. in diameter. The lines run across country, crossing rivers, valleys, mountains, highways, railways, farms, forest, and deserts. They are built in all kinds of terrain and under widely varied atmospheric conditions.

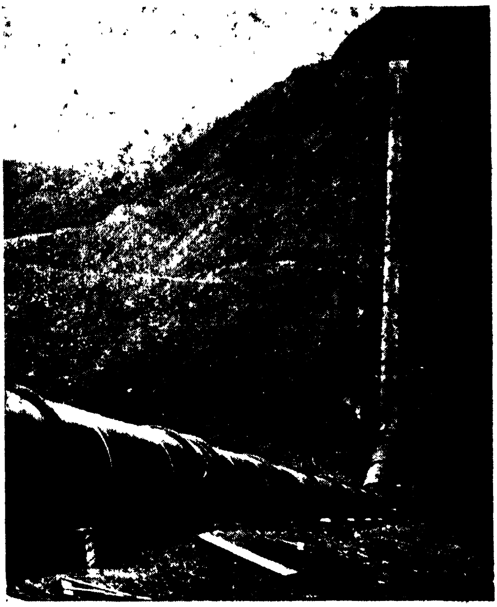


FIG. 21.—Welded 9 ft. diameter pipe (part of the 1,630 ft. Owyhee siphon). (*Courtesy of The Lincoln Electric Company.*)

Railroad Equipment.—Modern locomotives have welded fireboxes, and the most recent advance in steel gondola-car construction is welded fabrication. Several such cars were built a few years ago for test purposes in actual service, and all of them have more than fulfilled the builders' and users' anticipations. The principal feature of this modern car construction is less dead load per ton carrying capacity which results in decreased hauling costs and greater earnings per car mile.

Railroads are among the largest users of welding. The boiler shops weld in new firebox sheets, crown sheets, side sheets, door sheets, flue sheets, flues, and thermic siphons, as well as repair many of the original items that have given difficulty in service.

In the carshops, welding is used to apply reinforcing plates, bars, or straps to weakened portions of the car body and underframe.

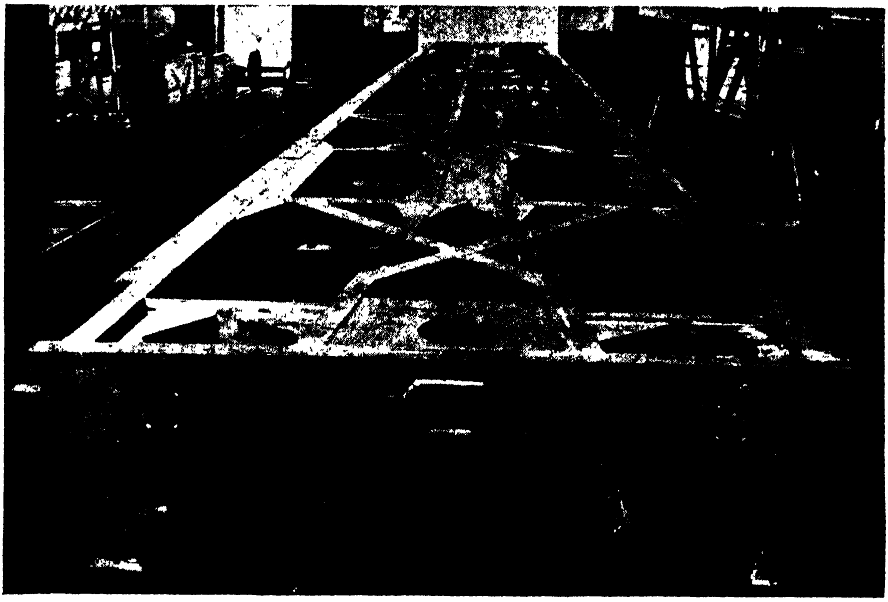


FIG. 22.—Welded underframe for railroad passenger car. (*Courtesy of The Lincoln Electric Company.*)

Large locomotive parts, such as frames, wheels, and cabs, that have become broken in service are repaired by welding.

There are many and widely varied types of welding operation in railroad machine shops. Most of this welding is applied to the building up of worn surfaces of such parts as crosshead guides, driving boxes, link action and parts, shafts, brake fulcrums, binders, cams, coupler parts, and guide bars. Also, frogs, crossings, and switches that have been removed from tracks owing to failure or severe wear are reclaimed by welding.

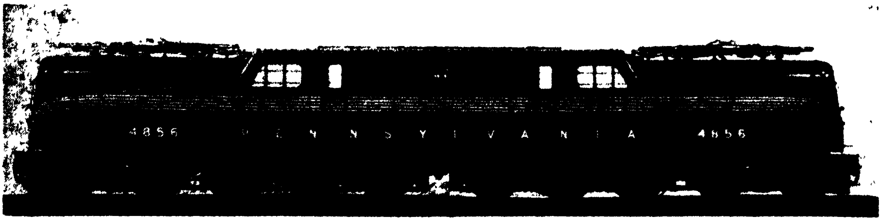


FIG. 23.—Electric locomotive with welded cab. (*Courtesy of The Lincoln Electric Company.*)

Ships, Barges, and Small Craft.—The efficiency of welded ship construction did not receive much widespread attention until the German government launched the "pocket battleship" *Deutschland* after the First World War. The *Deutschland* was limited to 10,000 tons by the

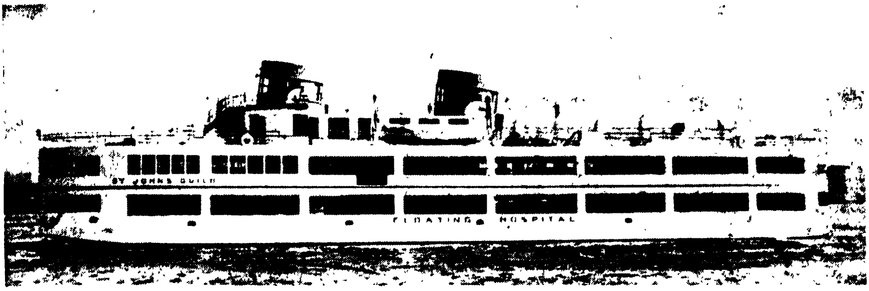


FIG. 24.—All-welded hospital ship. (*Courtesy of The Lincoln Electric Company.*)

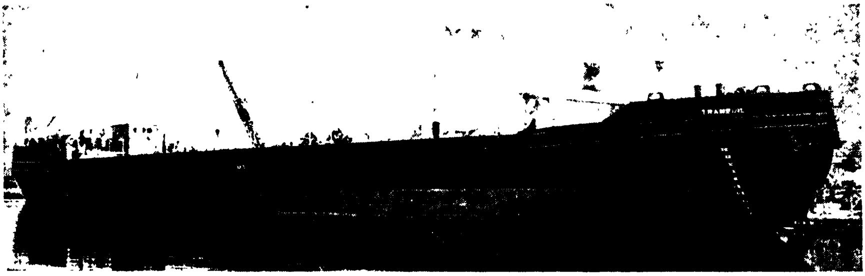


FIG. 25.—Welded tanker. (*Courtesy of General Electric Company.*)

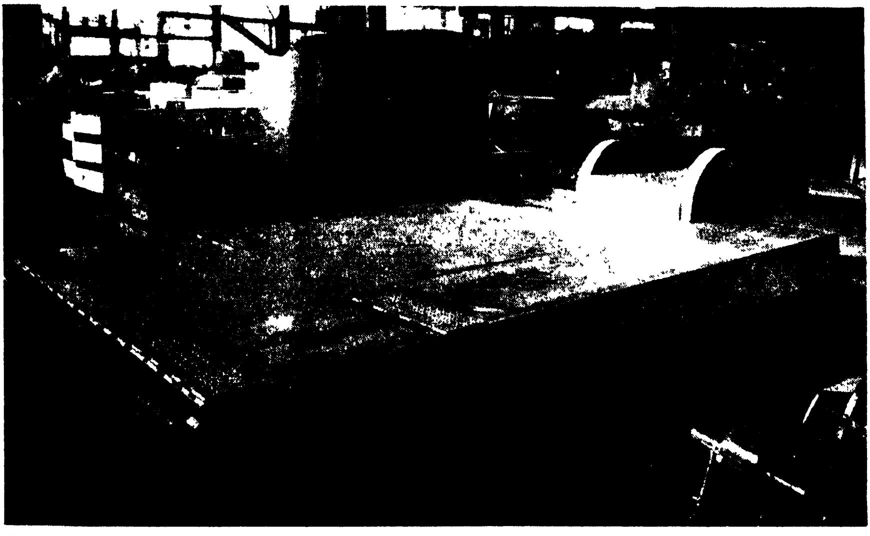


FIG. 26.—Welded frame for heavy-duty trailer. (*Courtesy of The Lincoln Electric Company.*)

Versailles Treaty, but the great reduction in weight effected by the use of welded, instead of riveted, construction made possible the equipping of the battleship with guns of greater size and range than was anticipated under the treaty.

During the past few years, great advances have been made in the application of welding to the shipbuilding industry. Several tankers, barges, and small ships have been fabricated with all-welded construction; and in the case of many other craft, including large ships, submarines, and other naval vessels, welding has been used extensively in their construction.

It has been estimated that savings of at least 3 per cent in cost and 17 per cent in weight may be effected by welded design.

Trucks and Trailers.—Dump bodies, tank bodies, and trailers are built by welding. A permanently tight, strong, and rigid construction is obtained for minimum weight. Smooth surfaces are also obtained which, in dump bodies, facilitate complete unloading.

CHAPTER III

WELDING TERMS AND THEIR DEFINITIONS

The American Welding Society (A.W.S.) has done much toward standardizing the terms used in the welding industry today. A number of the definitions and illustrations included in this chapter have been taken from literature issued by this body and are reprinted through its courtesy.

Acetylene: Colorless gaseous hydrocarbon, produced by the direct combination of carbon and hydrogen. It is usually produced by subjecting calcium carbide to the action of water.

Adapter: Device having, at one end, a socket into which a carbon or graphite electrode can be fitted and, at the other end, a wire-shaped section which can be inserted in any regular electrode holder (see Fig. 27).

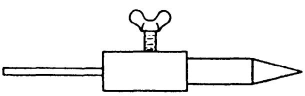


FIG. 27.—Adapter.

Device used to connect a pressure regulator to a cylinder whose valve has not been threaded "to match" the inlet connection of the regulator.

Adding material: Filler metal added in a joint; welding wire or welding rod.

Adhesion: Improper or imperfect unification or amalgamation of the edges of a joint; lack of fusion or lack of penetration.

Air-acetylene flame: Flame produced by the combustion of air and acetylene.

Air-acetylene welding: Gas-welding process wherein the welding heat is obtained from the air-acetylene flame.

Alignment: State of being in line.

Alloy: Substance composed of two or more metals or, by extension, of a metal and a nonmetal, intimately united, usually by being fused together and dissolving in each other, when molten.

All-weld-metal test specimen: Test specimen composed wholly of weld metal.

Alternating current: Electrical current that reverses its direction at regular intervals.

Alternating-current arc welding: Arc-welding process in which alternating current is the necessary power supply at the arc.

Aluminum: Bluish silver-white, lightweight, sonorous, ductile, malleable metal.

Amalgamation: Blending or combining of different metals into a uniform whole.

Ampere: Rate of flow of electricity; the practical unit of intensity of electrical current, being that produced by 1 volt acting through a resistance of 1 ohm.

Angle: Enclosed space, commonly measured in degrees, between two intersecting lines or surfaces.

Annealing: Heating and cooling operation for the purpose of removing gases and stresses; inducing softness; altering ductility, toughness, electrical, magnetic, or other physical properties; or refining the crystalline structure.

Anode: Positive pole, or terminal, of an electric source.

Anode drop: Voltage between the arc stream and the positive electrode.

Arc: State of an electrical current jumping across a gaseous gap that is part of the circuit.

Arc blow: Action of the arc jumping in various directions owing to a magnetic condition of the arc.

Arc brazing: Electric brazing process wherein the heat is obtained from an electric arc, formed between the base metal and an electrode or between two electrodes.

Arc flame: Yellow-colored flame that burns outside the arc stream.

Arc stream: Bluish-colored light stream that surrounds the arc core.

Arc-stream voltage: Voltage across the gaseous zone which varies with the length of the arc.

Arc voltage: Voltage across the arc, or the total sum of the arc-stream voltage, cathode drop, and anode drop.

Arc welding: Nonpressure (fusion) welding process wherein the welding heat is obtained from an electric arc formed either between the base metal and an electrode or between two electrodes.

Arc-welding machine: Source of current supply equipped with some means of controlling the welding current and voltage.

Asbestos: Grayish or greenish fibrous mineral that has the property of being incombustible, nonconducting, and chemically resistant.

Atomic-hydrogen welding: Alternating-current arc-welding process wherein the welding heat is obtained from an arc produced between two suitable electrodes in an atmosphere of hydrogen.

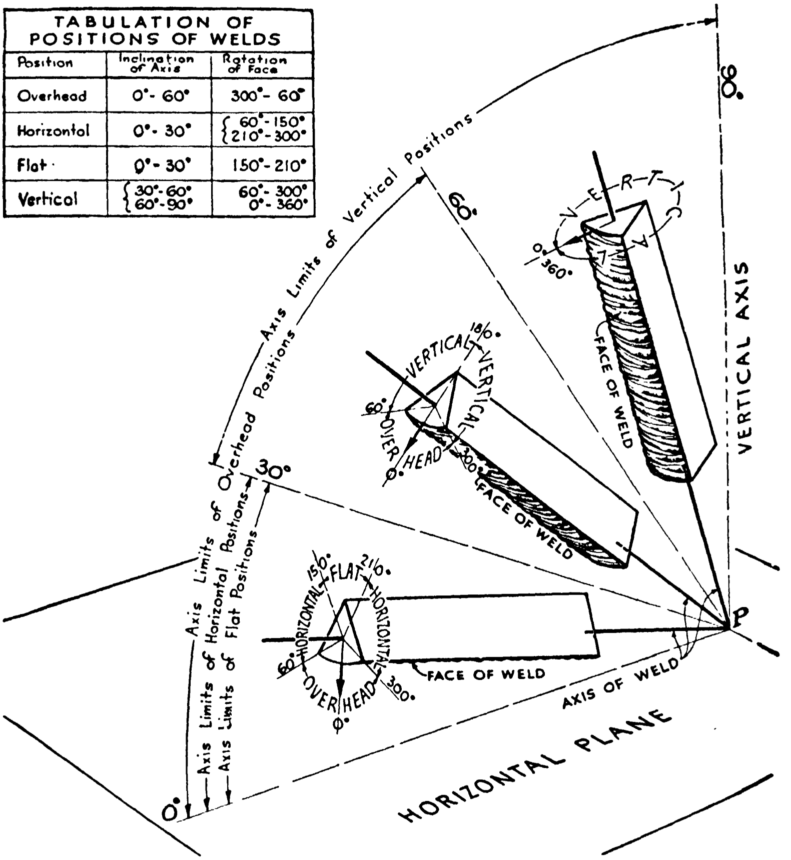
Automatic welding: Welding with equipment that automatically controls the entire welding operation (including feed, speed, oscillation, interruption, etc.).

Axis of weld: Line through the weld parallel to the root (see Fig. 28).

Backfire: Momentary recession of the flame into the torch tip followed by immediate reappearance or complete extinguishment; sometimes used as a synonym for "flashback."

Backhand welding: Technique of gas welding in which the flame is directed back toward complete weld or opposite to the progress of welding.

Backing strip: Material (metal, asbestos, carbon, etc.) backing up the root of the weld.



TABULATION OF POSITIONS OF WELDS

Position	Inclination of Axis	Rotation of Face
Overhead	0°- 60°	300°- 60°
Horizontal	0°- 30°	60°-150° 210°-300°
Flat	0°- 30°	150°- 210°
Vertical	30°-60° 60°-90°	60°- 300° 0°- 360°

The horizontal reference plane is taken to lie always below the weld under consideration.

Inclination of axis is measured from the horizontal reference plane toward the vertical.

Angle of rotation of face is measured from a line perpendicular to the axis of the weld and lying in a vertical plane containing this axis. The reference position (0°) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. The angle of rotation of the face of weld is measured in a clockwise direction from this reference position (0°) when looking toward point "P."

Fig. 28.—Positions of welds.

Back-step welding: Welding technique wherein the increments of weld metal are deposited opposite to the direction of progression.

Bare electrode (lightly coated electrode): Solid metal electrode with no coating other than that incidental to the manufacture of the electrode or with a light coating.

Base metal (parent metal): Metal to be welded or cut.

Base-metal test specimen: Test specimen composed wholly of base metal.

Bead weld: Type of weld made by one passage of the electrode or rod (see Fig. 29).

Beading (parallel beads): Technique of depositing weld metal without oscillation of the electrodes (see Fig. 30).

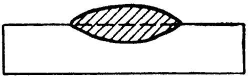


Fig. 29.—Bead weld.

Bend test: Angle through which the material can be bent without fracture, or the number of bendings around a predetermined diameter. Used especially to indicate the ductility of malleable metals.

Bevel: Angle that one surface or line makes with another when not at right angles.

Bevel angle: See Groove angle.

Bevel weld: See Groove weld.

Blacksmith welding: See Forge welding.

Blowhole: Void, hole, or cavity formed by trapped gas, dirt, grease, or any other foreign substance. See also Gas pocket.

Blowoff valve: Safety valve on an acetylene generator.

Blowpipe: Gas-welding or gas-cutting torch. See also Welding torch.

Bond: Junction of the weld metal and the base metal.

Bottle: See Cylinder.

Brass: Alloy consisting essentially of copper and zinc in variable proportions.

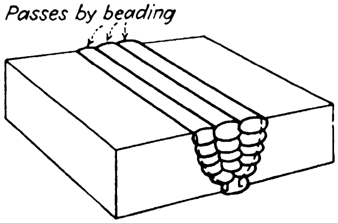


Fig. 30.—Beading.

Brazing: Group of welding processes wherein the filler metal is a nonferrous metal or alloy whose melting point is higher then 1000°F. but lower than that of the metals or alloys to be joined.

Brazing wire: Filler rod of bronze or brass used in brazing process.

Brinell number: Ratio of load on a sphere used to indent the material to be tested to the area of the spherical indentation produced.

B.t.u. (British thermal unit): Unit of measure of heat; quantity of heat required to raise temperature of 1 lb. water through 1°F.

Brittleness: Liability to sudden failure or the property of breaking without visible permanent deformation.

Bronze: Alloy consisting chiefly of copper and tin.

Buckling: Distortion caused by the heat of the welding process.

Build-up sequence: Deposition of weld metal in a groove by means of multiple passes.

Burning: Incorrect term often used in place of "cutting." See Cutting process.

Butt joint: Form of joint wherein the two plates to be welded are brought together in the same plane, edge to edge (see Fig. 31).

Butt resistance weld: Form of joint used in resistance welding wherein pieces having practically the same cross section are welded end to end, the weld being made by heating to a fusing temperature the entire areas of the butted surfaces and applying pressure (see Fig. 32).

Butt resistance welding: See Resistance butt welding.

Butt weld: Weld deposited in a butt joint (see Fig. 31).

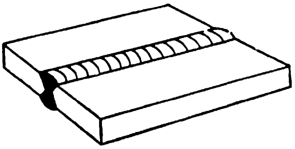


Fig. 31.—Butt joint. Types of welds applicable to butt joints: square groove, single-Vee groove, double-Vee groove (illustrated), single-bevel groove, double-bevel groove, single-U groove, double-U groove, single-J groove, double-J groove, butt (resistance).

Calcium carbide: Hard, opaque, crystalline substance consisting of one unit of mass of calcium, combined with two units of mass of carbon. (Used in generation of acetylene.)

Calking: Flowing a metal into a more compact mass by lightly hammering it with a roundnose tool.

Calking weld: Weld added to a joint merely to secure a tight joint that will not leak under prescribed pressure. It is not a strength weld.

Carbon: Element present in all organic compounds and occurring in nature in two distinct forms, diamond and graphite. (Produced in the form of charcoal, lampblack, coke, etc., by the action of heat on vegetable and animal tissues.)

Carbon arc: Arc maintained between a carbon electrode and the work, or between two carbon electrodes.

Carbon-arc cutting: Process of severing metals by melting with the heat of the carbon arc. Melting type of the cutting process.

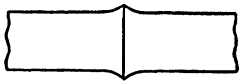


Fig. 32.—Slow butt resistance weld.

Carbon-arc welding: Arc-welding process wherein a carbon or graphite electrode or electrodes is used, with or without the use of filler metal.

Carbon dioxide: Heavy, colorless, and incombustible gas produced by the complete combustion of carbon.

Carbon electrode: Carbon or graphite rod through which current is conducted between the electrode holder and the arc.

Carbonizing flame: See Carburizing flame.

Carbon monoxide: Odorless, colorless, and very poisonous gas produced by the incomplete combustion of carbon.

Carburizing (Carbonizing) flame: Gas flame having the property of introducing carbon into the metal heated.

Cast iron: Iron produced in a blast furnace and cast into molds. It contains so much carbon or its equivalent that it is not malleable at any temperature.

Cast-iron thermit: Thermit mixture containing additions of ferrosilicon and mild steel.

Cathode: Negative pole or terminal of an electric source.

Chain intermittent fillet weld: Weld of broken continuity made up of short equal beads symmetrically disposed with respect to the center of gravity of the weld itself (see Fig. 33).

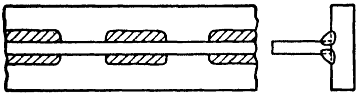


Fig. 33.—Chain intermittent fillet weld.

Chemical dip brazing: Dip-brazing process wherein the filler metal is added to the joint before immersion in a bath of molten chemicals.

Chromium: Grayish-white metal, hard and brittle and resistant to corrosion.

Closed joint: Joint having its edges or surfaces in contact during welding; that is, one in which there is no space between the parts being joined (see Fig. 34).

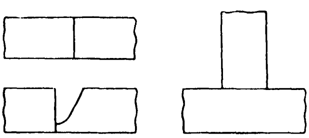


Fig. 34.—Closed joints.

Coated (shielded arc) electrode: Metal electrode that has a relatively thick covering material serving the dual purpose of stabilizing the arc and improving the properties of the weld metal.

Cohesion: Condition existing in a weld when molecules of parent metal and added material are thoroughly joined.

Collar: Reinforcing metal of a nonpressure thermit weld.

Composite electrode: Electrode with or without a flux having more than one filler material combined mechanically.

Composite joint: Joint wherein welding is used in conjunction with a mechanical joint.

Composite weld: Weld that must have both strength and tightness.

Compressive strength: See Tensile strength.

Concave weld: Weld whose top layer finishes below the plane of the surrounding material (see Fig. 35).

Concurrent heating: Supplementary heat applied to a structure during the course of welding.

Cone: Conical part of a gas flame that is next to the orifice of the tip.

Constant-current welding source: Source of electric power for arc-welding purposes that, when adjusted to give rated current output with normal arc voltage, will automatically maintain this current output within 5 per cent of the rated value, with a variation in arc voltage of 10 per cent above or below the normal arc voltage, and that has time of recovery of not more than 0.3 sec.

Constant-power welding source: Source of electric power for arc-welding purposes that, when adjusted to give rated power output with normal arc voltage, will automatically maintain this power output within 5 per cent of the rated value, with a variation in arc voltage of 10 per cent above or below the normal arc voltage, and that has time of recovery of not more than 0.3 sec.

Constant-voltage welding source: Source of electric power for arc-welding purposes that automatically maintains its voltage within 5 per cent of the rated full-load setting over the range from full load to no load and that has a time of recovery of not more than 0.3 sec.

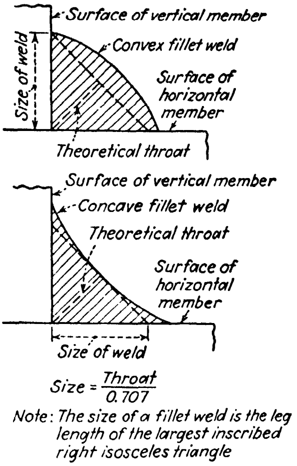
Contact jaw: Electrical terminal used in a resistance-butt-welding machine to clamp securely the parts to be welded and to conduct the electric current to these parts.

Content: Percentage of any element contained in a pure metal or alloy.

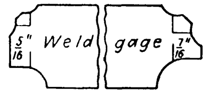
Continuity: Linear distribution of a weld in a welded joint.

Continuous weld: Weld that extends continuously for its entire length.

Contraction: Shrinkage of metals upon cooling.


Surface of vertical member
Convex fillet weld
Size of weld
Surface of horizontal member
Theoretical throat
Surface of vertical member
Concave fillet weld
Theoretical throat
Surface of horizontal member
Size of weld
Size = Throat / 0.707
Note: The size of a fillet weld is the leg length of the largest inscribed right isosceles triangle

(a)-Size of fillet weld



(b)-Typical fillet weld gage

Fig. 35.—Size of fillet weld and fillet weld gage.

Convex weld: Weld whose top layer finishes above the plane of the surrounding material (see Fig. 35).

Convexity ratio: Ratio of the reinforcement to the throat of a weld (see Fig. 36).

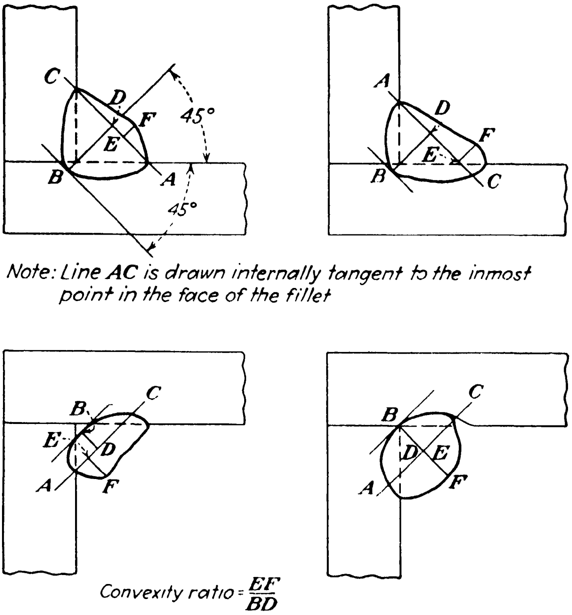
Copper: Common metal, reddish in color, ductile, malleable, and very tenacious, and one of the best conductors of heat and electricity.

Corner joint: Joint formed by placing the edge of one member on an edge or surface of another member in such a manner that neither member extends behind the outer surface plane of the other member joined (see Fig. 37).

Coulomb: Unit of quantity of electricity; that quantity of electricity which passes a cross section of the conductor in 1 sec. when the rate of flow is 1 amp.

Covered (shielded arc) electrode: See Coated electrode.

Cover glass: Clear glass used to protect the lens in goggles, face shields, and helmets from spattering material.



Note: Line AC is drawn internally tangent to the inmost point in the face of the fillet

Convexity ratio = $\frac{EF}{BD}$

FIG. 36.—Convexity ratio.

Crater: Depression at the termination of an arc weld.

Critical temperature: Temperature at which any of the following phenomena might occur in a metal: hardening upon quenching; loss of magnetism; refining of the coarse grain upon cooling.

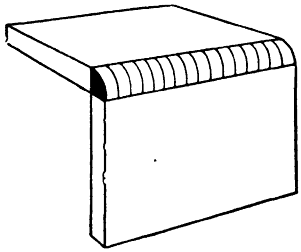


FIG. 37.—Corner joint. Types of welds applicable to corner joints: fillet (illustrated), square groove, single-Vee groove, single-bevel groove, double-bevel groove, single-U groove, single-J groove, double-J groove, projection (resistance).

Cutting process: Chemical-reaction type—see Gas cutting. Melting type—see Carbon-arc cutting and Metallic-arc cutting.

Cutting tip (nozzle): Gas-torch tip especially adapted for cutting.

Cylinder (bottle): Portable container used for storage of a compressed gas.

Denseness: Compactness; lack of porosity.

Deoxidizing agent: Any element capable of taking away oxygen.

Deposited metal: Metal that has been added by a welding process.

Deposition efficiency: Ratio of the weight of deposited metal to the net weight of the electrodes consumed (exclusive of stubs).

Depth of fusion: See Penetration.

Dip brazing: Group of brazing processes wherein the heat is obtained from a bath of molten metal or chemical; the filler metal may or may not be obtained from the bath.

Direct current: Practically nonpulsating electrical current made to flow in one direction only.

Direct-current arc welding: Arc-welding process wherein the power supply at the arc is direct current.

Distortion: Warping, or the state of being out of line or place.

Double-bevel groove weld: See Groove weld.

Double groove weld: See Groove weld.

Double-J groove weld: See Groove weld.

Double-U groove weld: See Groove weld.

Double-Vee groove weld: See Groove weld.

Drawing the arc: Contacting (touching) of the electrode to the work, thus completing the circuit, and then quickly withdrawing it a short distance, so as to form an arc between the electrode and work.

Edge joint: Joint formed when the edges of the contacting base-metal parts are in the same plane, the contacting parts being on the same side of the plane (see Fig. 38).

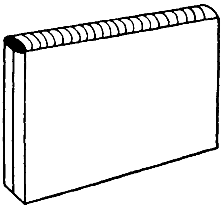


Fig. 38.—Edge joint. Types of welds applicable to edge joints: bead (illustrated), single-Vee groove, single-U groove.

Edge preparation: Grooving of an edge to the desired shape prior to the actual welding (see Fig. 39).

Edge weld: Weld uniting the parts of an edge joint.

Effective length of weld: Length of the correctly proportioned cross section of a weld.

Elastic limit: Limit of stress within which the deformation completely disappears after the removal of stress, that is, within which no set deformation remains.

Elasticity: Power possessed by a body to resume its original form after removal of the force that has produced a change in that form.

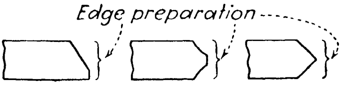


Fig. 39.—Edge preparation.

Electric brazing: Group of brazing processes wherein the heat is obtained from electric current.

Electric conductivity: Electrical conducting power of a unit length of a substance per unit of cross-sectional area.

Electrode:

1. *Metallic-arc welding.* Filler metal in the form of a wire or rod, either bare or covered, through which current is conducted between the electrode holder and the arc.
2. *Carbon-arc welding.* Carbon or graphite rod through which current is conducted between the electrode holder and the arc.

3. *Atomic-hydrogen arc welding.* One of two tungsten rods between the points of which the arc is maintained.
4. *Resistance welding.* Bar, wheel, or die through which the current is conducted and the pressure applied to the work.

Electrode holder: Device used for mechanically holding the electrode.

Electrode tip: Replaceable tip of metal on an electrode, having the electrical and physical characteristics required for spot and projection welding.

Electrolysis: Chemical decomposition accompanying the passage of electric current through a solution or a fused salt.

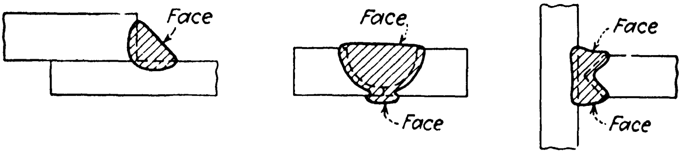


Fig. 40.—Face of welds.

Electrolyte: Conducting liquid between anode and cathode in an electrolytic process.

Equiaxed grain: Unstrained grain having approximately equal dimensions in all directions.

Etching: Process of preparing the polished surface of a metal for examination and test by treating it with some acid.

Expansion: State of increase in the dimensions of metals due to a heat condition.

Face of weld: Exposed surface of a weld (see Fig. 40).

Face shield: See Hand shield.

Fatigue resistance: Resistance of a material to a load that is applied and removed in whole or in part many times and at short intervals.

Ferrite: Term applied to the iron in steel as distinguished from the usual term "iron" or "steel" which refers to the whole mass.

Filler metal: Material to be added in making a weld.

Fillet weld: Weld positioned between two surfaces at right angles to one another (see Fig. 35).

Fillet-weld size: See Size of fillet weld.

Filter lens (lens): Colored glass used in goggles, helmets, and shields to exclude harmful light rays.

Fin: See Flash.

Fixed joint: Joint so designed that the component members are not permitted to move during welding.

Flash (fin): Metal expelled from a joint made by the resistance-welding process.

Flash butt welding (resistance flash butt welding): Resistance-butt-welding process wherein the potential is applied before the parts are brought in contact and the heat is derived principally from a series of arcs between the parts being welded.

Flashback: Recession of the flame into or behind the mixing chamber of the torch. See also Backfire.

Flat position of welding: See Flat weld.

Flat weld (flat position of welding): Weld made in a horizontal plane or plane inclined at an angle of 30 deg. or less to the horizontal, with the welding end of the electrode pointing generally downward from above (see Fig. 28).

Flexible materials: Materials that have a low modulus of elasticity. They can be deformed considerably by bending, twisting, etc., within the elastic limit of material.

Flush weld: Weld whose top layer is finished almost flat or so that it lies in the same plane as on the adjoining material; weld made with a minimum reinforcement (see Fig. 41).

Flux: Fusible material or gas used to dissolve and/or prevent the formation of oxides, nitrides, or other undesirable inclusions formed in welding.

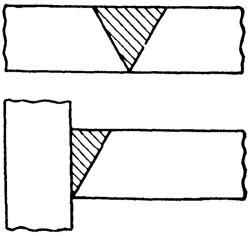


FIG. 41.—Flush welds.

Flux-coated electrode: Metallic electrode entirely coated with flux.

Forehand welding: Gas-welding technique wherein the flame is directed toward the progress of welding.

Forge welding (blacksmith, roll, or hammer welding): Group of pressure-welding processes wherein the parts to be welded are brought to suitable temperature by means of external heating and the weld is consummated by pressure or blows.

Forging thermit: Thermit mixture in which carbon, manganese, nickel, and mild steel have been included.

Fracture: Surface across which the break or crack has occurred.

Free-bend test specimen: Specimen that is tested by bending without constraint of a jig.

Freezing: Sticking of a metallic electrode to the base metal when striking an arc.

Frequency: Number of complete cycles of current produced by an a.c. generator per second.

Full fillet weld: Fillet weld whose size is equal to the thickness of the thinner member joined.

Furnace brazing: Brazing process wherein the heat is obtained from a furnace.

Fuse: To liquefy by heat or to melt.

Fusibility: Ease with which a body may be melted.

Fusible plug: Plug of suitable metal or alloy that closes the discharge channel of a gas cylinder and is intended to melt away at a predetermined temperature to permit the escape of gas in the cylinder.

Fusion welding: Group of processes in which metals are welded together by bringing them to the molten state at the surfaces to be joined, with or without the addition of filler metal and without the application of mechanical pressure or blows.

Fusion zone: That section of area of the weld-metal zone which borders on the unmelted base, or parent, metal.

Gas brazing: Brazing process wherein the heat is obtained from a gas flame.

Gas cutting: Process of severing ferrous metals by means of the chemical action of oxygen on elements in the base metal. Chemical-reaction type of the cutting process.

Gas pocket (blowhole): Cavity in a weld caused by gas inclusion.

Gas welding: Nonpressure- (fusion-) welding process wherein the welding heat is obtained from a gas flame.

Goggles: Colored glasses used to protect eyes during welding.

Grain: Groups of crystals present in solid metals.

Graphite: Variety of carbon.

Graphite electrode: Electrode made up of the same base and binder as those used for hard amorphous carbon but that has been baked long enough at a sufficiently high temperature to graphitize the binder.

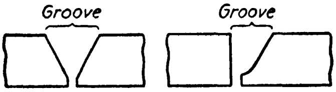


Fig. 42.—Groove.

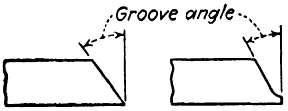


Fig. 43.—Groove angle.

Groove: Formation of a channel between the plates to be joined (see Fig. 42).

Groove angle (bevel angle): Enclosed space between the surface of a prepared edge and a reference line (see Fig. 43).

Groove weld: Weld deposited in special grooves. (The nine main types of groove weld are illustrated in Figs. 44 to 53.)

Ground connections (welding ground): Side of the circuit opposite the welding electrode.

Guided-bend test: Bending test wherein the specimen is bent to a definite shape by means of a jig.

Hammer welding: See Forge welding.

Hand shield (face shield): Protective device used in arc welding for shielding the face and neck, equipped with suitable filter-glass lens and designed to be held by hand.

Hardening: Heating to a critical temperature and then suddenly cooling by quenching.

Hard facing: Deposition of hard metal, alloy overlays, or veneers to iron and steel parts.

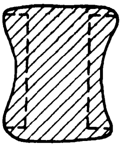


Fig. 44.—Square groove weld.

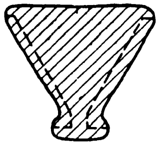


Fig. 45.—Single-Vee groove weld.

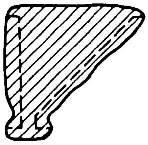


Fig. 46.—Single-bevel groove weld.

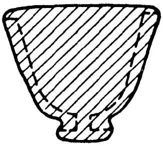


Fig. 47.—Single-U groove weld.

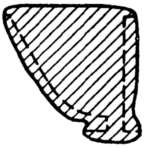


Fig. 48.—Single-J groove weld.

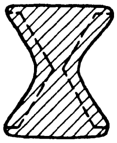


Fig. 49.—Double-Vee groove weld.

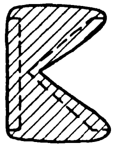


Fig. 50.—Double bevel groove weld.

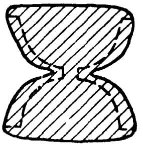


Fig. 51.—Double-U groove weld.

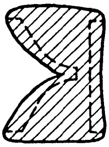


Fig. 52.—Double-J groove weld.

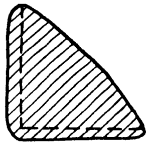


Fig. 53.—Fillet weld.

Hard materials: Materials that offer great resistance to indenting or scratching.

Hardness: Ability of one substance forcibly to penetrate another substance without fracture of either.

Heat-affected zone: Portion of the base metal whose structure or properties have been altered by the heat of welding or cutting.

Heat conductivity: Heat-conducting power of a unit length or thickness of a substance per unit of cross-sectional area.

Heating gate: Opening in a thermit mold through which the parts to be welded are preheated.

Helmet shield: Protective device used in arc welding for shielding the face and neck, equipped with suitable filter-glass lens and designed to be worn on the head.

Horizontal position of welding: See Horizontal weld.

Horizontal weld (horizontal position of welding): Weld deposited in a vertical plane or in a plane nearly vertical, with the line of weld running horizontally.

Hot-short: Brittle condition of metals at red heat due to a high sulphur and phosphorus content.

Impact resistance: Shock-resisting qualities of a material.

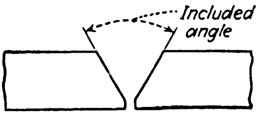


Fig. 54.—Included angle

Included angle: Included space, commonly measured in degrees, between the edges of two members of a joint (see Fig. 54).

Induction brazing: Electric-brazing process wherein the heat is obtained from induced current.

Intermittent weld: Weld whose continuity is broken by unwelded spaces.

Interrupted spot welding: Spot-welding process wherein fusion is accomplished by means of successive applications of electrical energy between contact electrodes during a single application of pressure to the electrodes.

Iron: Silver-white metallic element, malleable, ductile, strongly attracted by magnets, and readily oxidized in moist air.

J groove weld: See Groove weld.

Jig (welding jig): Device that holds, in established relationship, the parts to be welded into an assembly and that may provide for partial or complete control of the residual heat effects of welding.

Joint: That portion of a structure in which separate base-metal parts are joined.

Joule: Unit of work. (Practically, the energy expended in 1 sec. by an electric current of 1 amp. in a resistance of 1 ohm.)

Kerf: Space from which the metal has been removed by a cutting process.

Kilovolt-ampere: See Kva.

Kilowatt: One thousand watts.

Kva. (kilovolt-ampere): $\frac{\text{Volts} \times \text{amperes}}{1,000}$

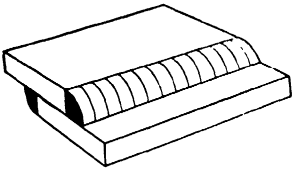


FIG. 55.—Lap joint. Types of welds applicable to lap joints: fillet (illustrated), plug, slot, spot (resistance), seam (resistance), projection (resistance).

Laminated: Sheet metal laid in layers.

Lap joint: Form of joint obtained by the overlapping of base-metal parts, the overlapping surfaces being in the same plane (see Fig. 55).

Lap weld: Weld deposited in a lap joint, so that it binds the edge or edges of one plate to the faces of the other plate.

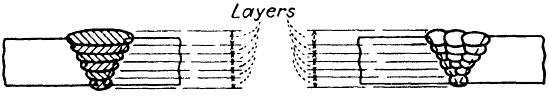


FIG. 56.—Layers.

Layer: Stratum of weld metal consisting of one or more beads depending on the size of the weld and the welding technique used (see Fig. 56).

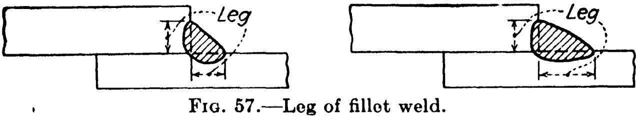


FIG. 57.—Leg of fillet weld.

Leg of fillet weld: One of the fusion surfaces of a fillet weld (see Fig. 57).

Length of weld: Lineal dimension of the unbroken length of a weld.

Lens: See Filter lens.

Lightly coated electrode: See Bare electrode.

Locked-up stress: See Residual stress.

Longitudinal seam: Seam that extends lengthwise.

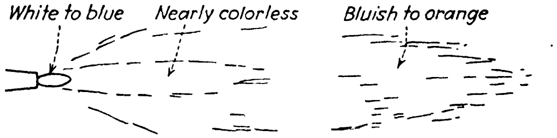
Magnetism: Magnetic force exerted by a unit volume of a substance under a standard magnetizing force.

Malleability: Property of being permanently deformed by compression without rupture.

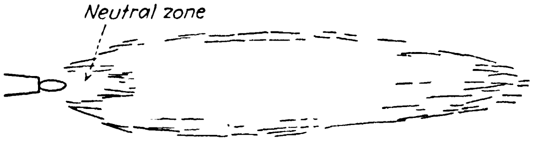
Manifold: Multiple header for connection of individual gas cylinders or torch supply lines.

Manual weld: Weld wherein the arc is controlled or the torch is manipulated by hand.

Melting rate: Weight of electrode consumed in a unit of time.



Flame as seen without welders goggles



Flame as seen with welders goggles

FIG. 58.—Neutral flame.

Melting ratio: Ratio of the volume of weld metal below the original surface of the base metal to the total volume of the weld metal.

Metal-dip brazing: Dip-brazing process wherein the filler metal is obtained from the molten metal bath.

Metallic-arc cutting: Process of severing metals by melting with the heat of the metal arc. Melting type of the cutting process.

Metallic-arc welding: Arc-welding process wherein the electrode supplies the filler metal in the weld.

Metallic electrode: See Electrode.

Micrograph: Graphic reproduction or the picture of any object magnified more then ten times its original size.

Mild steel: In general, term applied to steels in the lower carbon ranges.

Mixing chamber: That part of a gas-welding or -cutting torch wherein the gases are mixed for combustion.

Modulus of elasticity: Ratio of increment of unit stress to increment of unit deformation within the elastic limit.

Monel metal: Alloy consisting mainly of two-thirds nickel and one-third copper.

Multiple resistance welding: Resistance-welding process wherein two or more separate welds are made simultaneously.

Neutral flame: Gas-welding flame in which there is no excess of either oxygen or acetylene (see Fig. 58).

Nickel: Grayish-white ductile metal.

Nonferrous metals: Metals that do not contain any ferrite or iron.

Nonpressure welding: Group of welding processes wherein the weld is made without pressure.

Nonrigid joint: Joint designed so that its component parts are free to move during welding.

Normalizing: Refining of the grain structure of a metal or alloy by proper heat-treatment.

Nozzle: See Cutting tip.

Ohm: Unit of resistance to the passage of an electric current.

Ohm's law: $\text{Current flow} = \dfrac{\text{electromotive force}}{\text{resistance}}$

$$I = \frac{E}{R}$$

or

$$\text{Electromotive force} = \text{current flow} \times \text{resistance}$$

$$E = I \times R$$

or

$$\text{Resistance} = \frac{\text{electromotive force}}{\text{current flow}}$$

$$R = \frac{E}{I}$$

Open-circuit voltage: Voltage across the electrodes of a welding circuit when no current is flowing.

Open joint: Joint whose edges and surfaces are spaced apart (see Fig. 59).

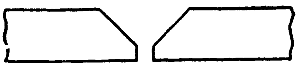


FIG. 59.—Open joint.

Overhead position of welding: See Overhead weld.

Overhead weld (overhead position of welding): Weld deposited on a horizontal plane or on a plane inclined at no more than 30 deg. to the horizontal, with the electrode being pointed generally upward.

Overlap (Roll): Protrusion of weld metal at the toe of a weld beyond the limits of fusion (see Fig. 60).

Oxidation: Chemical reaction between oxygen and some other elements, resulting in oxides.

Oxide: Compound of oxygen and some other element. A term usually applied to rust, corrosion, coating, or scale.

Oxidizing flame: Gas-welding flame wherein the portion used has an oxidizing effect (see Fig. 61).

Oxyacetylene flame: Flame produced by the combustion of a mixture of oxygen and acetylene.

Oxyacetylene welding: Gas-welding process wherein the welding heat is obtained from the combustion of oxygen and acetylene.

Oxygen: Colorless and odorless chemical element or gas; one of the chief constituents of the atmosphere.

Oxygen lance: Device used especially for piercing holes in large masses. (Its operation is similar to that of the oxyacetylene torch.)

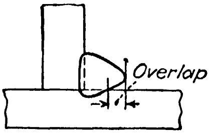
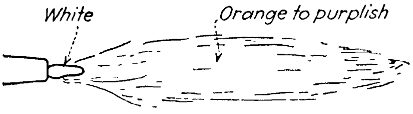


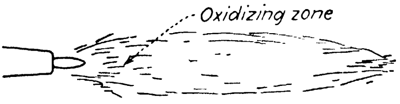
Fig. 60.—Overlap.

Oxyhydric torch: Torch used for the mixing and combustion of oxygen and hydrogen.

Oxyhydrogen flame: Flame produced by the combustion of a mixture of oxygen and hydrogen.



Flame as seen without welders goggles



Flame as seen with welders goggles

Fig. 61.—Oxidizing flame.

Oxy-other-fuel gas welding: Gas-welding process wherein the welding heat is obtained from the combustion of oxygen and any fuel gas other than acetylene.

Padding: Deposition of weld metal by running beads in such a way that the beads are united with one another to form a solid mass.

Parallel beads: See Beading.

Parent metal: See Base metal.

Pass: Weld metal deposited by one general progression along the axis of a weld (see Fig. 62).

Pass sequence: Method of depositing a weld with respect to its length.

Peening: Mechanical working of metal by means of hammer blows.

Penetration (depth of fusion or weld penetration): Distance in a weld from the original surface of the base metal to that point at which fusion ceases (see Fig. 63).

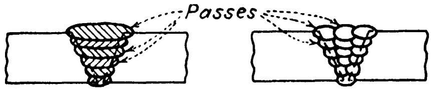


Fig. 62.—Passes.

Percussive welding: Resistance-welding process utilizing stored up electrical energy suddenly discharged.

Pickling: Soaking of metal in acid solution in order to free the surface of the metal from rust, scale, or other foreign substances.

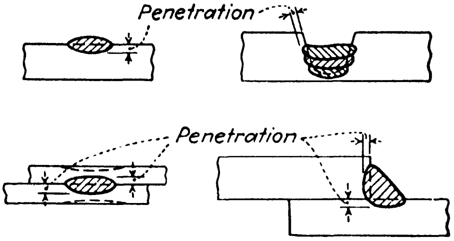


Fig. 63.—Penetration.

Piping—positions for welding:

1. *Horizontal fixed position.* When the axis of the piping is in a horizontal position (within the same limits as those specified for the axis of welds in Fig. 28) and the piping is not rotated during welding. In this position, welding is done in the flat, vertical, and overhead positions, as defined in Fig. 28.
2. *Horizontal rolled position.* When the axis of the piping is in a horizontal position (within the same limits as those specified for the axis of welds in Fig. 28) and the piping is rotated during welding. In this position, welding is done in the flat position, as defined in Fig. 28.
3. *Vertical position.* When the axis of the piping is in a vertical position (within the same limits as those specified for the axis of welds in Fig. 28) and the piping may or may not be rotated during welding. In this position, welding is done in the horizontal position, as defined in Fig. 28.

Plain thermit: Mixture of iron oxide and finely divided aluminum.

Plastic materials: Materials capable of undergoing considerable permanent deformation under compressive stresses.

Plug weld: Weld used to join metals by welding through a hole in one of the members being joined (see Fig. 64).

Poke welding: Spot-welding process wherein pressure is applied manually to one electrode only.

Polarity: Direction of flow of current.

Pole: One of the two terminals of an electrical generator.

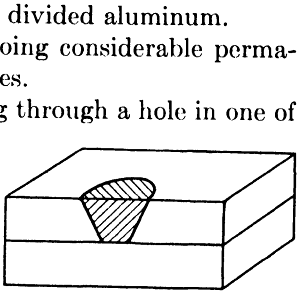


Fig. 64.—Plug weld.

Pool: Small body of molten metal, or puddle, created by the heat of the welding process.

Porosity: Presence of gas pockets or inclusions.

Positions of welds: Position in which weld metal is deposited (see Fig. 28).

Postheating: Heat applied subsequent to welding or cutting operations.

Power factor: Ratio of true watts to apparent watts.

Preheating: Heat applied prior to welding or cutting operations.

Pressure regulator: Device designed to reduce and regulate the pressure of gases used for welding and cutting.

Pressure thermit welding: Pressure-welding process wherein the heat is obtained from the liquid products of a thermit reaction.

Pressure welding: Group of welding processes wherein the weld is consummated by pressure.

Primary leads: Wires that connect the primary windings of the transformer of an electric machine with the shop circuit.

Progressive spot welding: Resistance spot-welding process wherein two or more spot welds are made automatically one after the other by the actuation of a single control device.

Projection spot weld: See Fig. 65.

Projection spot welding: Resistance-welding process wherein localization of heat between two surfaces or between the end of one member and surface of another is effected by projections.

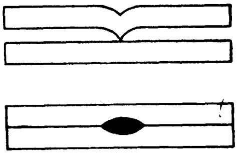


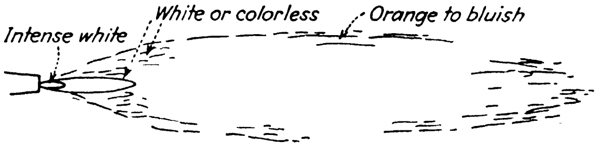
Fig. 65.—Projection spot weld.

Puddling: Mixing of the puddle of molten metal with the filter rod.

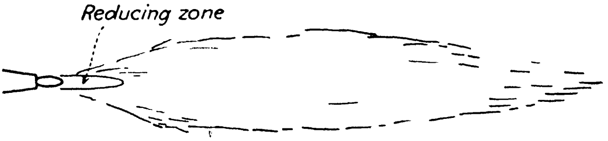
Radiograph: X-ray photograph.

Rate of deposition: Weight of weld metal deposited in a unit of time.

Rate of flame propagation: Speed at which a flame travels through a mixture of gases.



Flame as seen without welders goggles



Flame as seen with welders goggles

Fig. 66.—Reducing flame.

Reducing flame: Gas-welding flame wherein the portion used has a reducing effect (see Fig. 66).

Refined zone: That portion of the base metal bordering on the fusion zone in which there has been a grain refinement due to the welding heat.

Reinforcement of weld: That portion of the weld metal built up above the general surface of the two abutting members that are being welded together (see Fig. 67).

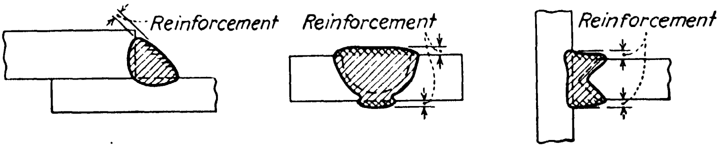


FIG. 67.—Reinforcement of welds.

Residual stress (locked-up stress): Stress remaining in a structure or member as a result of thermal or mechanical treatment, or both.

Resilience: Energy of elasticity of a body; energy that is stored in a material under strain within its elastic limit which causes it to resume its original shape when the external strain is removed. Also, simply defined as the springiness of a body.

Resistance brazing: Electric-brazing process wherein the heat is obtained from the resistance to the flow of an electric current.

Resistance butt weld: See Fig. 32.

Resistance butt welding (butt resistance welding): Group of resistance-welding processes wherein the fusion occurs simultaneously over the entire contact area of the parts being joined.

Resistance flash butt welding: See Flash butt welding.

Resistance-welding time: Duration of the welding current.

Resistor: Electrical resistance used to regulate the arc amperage.

Reversed polarity: Arrangement of d.c. arc-welding leads wherein the work is the negative pole and the electrode is the positive pole in the arc circuit.

Rigid joint: Joint in which the surfaces of the parts to be united are in the same plane and the edges are tacked in a parallel position before welding, with one or both of the parts being free to move (see Fig. 68).

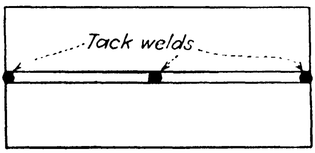


FIG. 68.—Rigid joint.

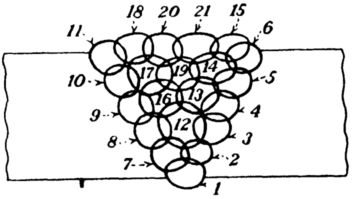


FIG. 69.—Rigid string welding.

Rigid string welding: Metallic-arc-welding process in which the weld metal is deposited in layers composed of strings of beads applied directly to the face of the bevel and thereafter the building up is done toward the center of the joint (see Fig. 69).

Ripple weld: Weld whose top surface lies in ripples, having much the same appearance as little waves on a body of water.

Roll: See Overlap.

Roll welding: See Forge welding.

Root: Section at the bottom of the cross-sectional space provided to contain a weld.

Root of weld: Section of the weld that is contained at the root of a joint (see Fig. 70).

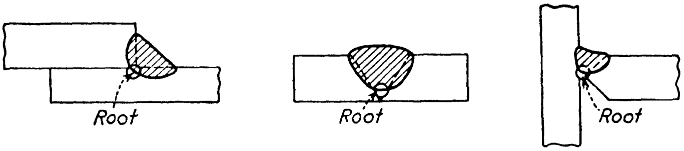


FIG. 70.—Root of welds.

Root edge: See Fig. 71.

Root face: See Fig. 72.

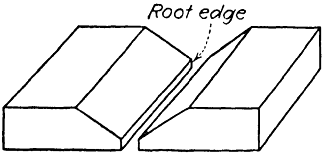


FIG. 71.—Root edge.

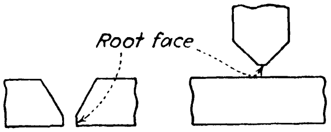


FIG. 72.—Root face.

Root opening: Amount of space between the parts to be united (see Fig. 73).

Root radius: See Fig. 74.

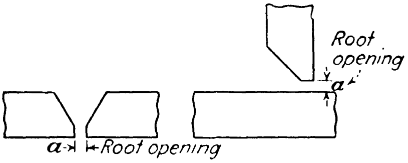


FIG. 73.—Root opening.

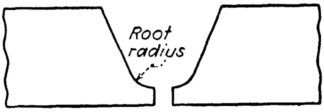


FIG. 74.—Root radius.

Sandblast: Process of cleaning surfaces by using fine sand under pressure.

Sand holes: Voids found in castings.

Scale: Term often applied to the coating of oxide that forms over the surface of iron or steel.

Scarf: Chamfered surface of a joint.

Seal weld: Weld used primarily to obtain tightness.

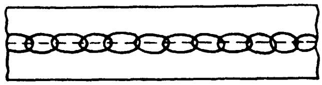


FIG. 75.—Seam weld.

Seam: Term sometimes applied to the line of the weld or to the edges of the metal joined.

Seam weld: See Fig. 75.

Seam welding: Resistance-welding process wherein overlapping or tangent spot welds are made progressively.

Semiautomatic metallic-arc weld: Weld made with equipment that automatically controls the feed of the electrode—the manipulation of the electrode being controlled by hand.

Series welding: Resistance-welding process wherein two or more welds are made simultaneously in a single welding circuit with the total current passing through every weld.

Shearing strength: See Tensile strength.

Shielded-arc electrode: See Coated electrode.

Shielded arc welding: Welding process in which the arc and the molten weld metal are protected from the gases in the atmosphere by a shielding medium.

Shielded metallic-arc welding: Metallic-arc-welding process wherein the arc and weld metal are protected from the atmosphere by a shielding medium.

Silver-alloy brazing (silver soldering): Brazing process wherein a silver alloy is used as a filler metal.

Silver soldering: See Silver-alloy brazing.

Single-bevel groove weld: See Groove weld.

Single groove weld: See Groove weld.

Single-J groove weld: See Groove weld.

Single-U groove weld: See Groove weld.

Single-Vee groove weld: See Groove weld.

Size of fillet weld: Leg length of the largest inscribed isosceles right triangle (see Fig. 35).

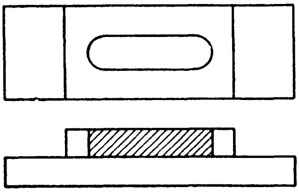


FIG. 76.—Slot weld.

Size of groove weld: Depth of the groove. Where fusion materially exceeds the groove depth, the size of the weld is the depth of the groove plus the depth of the fusion.

Slag inclusion: Nonmetallic substance entrapped in a weld.

Slot weld: See Fig. 76.

Soft material: Materials that offer little resistance to indenting or scratching.

Spatter loss: Difference in weight between the amount of electrode deposited and the weight of the electrode consumed (melted).

Speed of welding: Comparative rate of travel of the electrode or filler rod.

Spot weld: See Fig. 77.

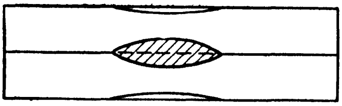


FIG. 77.—Spot weld.

Spot welding: Resistance-welding process wherein the fusion is confined to a relatively small portion of the area of the lapped parts to be joined.

Square groove weld: See Groove weld.

Staggered intermittent fillet weld: See Fig. 78.

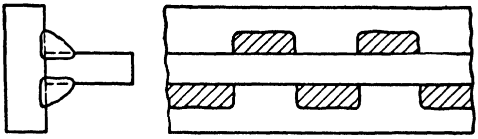


FIG. 78.—Staggered intermittent fillet weld.

Stainless steel: Alloy consisting mainly of iron, chromium, and nickel.

Steel: Alloy consisting mainly of iron and carbon.

Stiff materials: Materials that have a high modulus of elasticity. They deform little, if subjected to stresses not exceeding the elastic limit.

Straight polarity: Arrangement of d.c. arc-welding leads wherein the work is the positive pole and the electrode is the negative pole of the arc circuit.

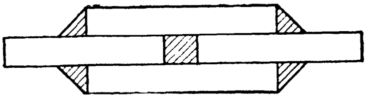


FIG. 79.—Strap weld.

Strap weld: Weld in which the seam is reinforced by any form or shape to add strength and stability to the joint or plate (see Fig. 79.)

Strength: Resistance to strain.

Strength weld: Weld used mainly to ensure the complete development of the strength of the joint.

Stress-relief heat-treatment: Often misnamed "normalizing" or "annealing," it is the uniform heating of a structure or part thereof to the proper temperature in order to relieve the major portion of the residual stresses, followed by uniform cooling.

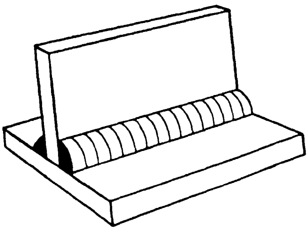


FIG. 80.—Tee joint. Types of welds applicable to Tee joints: fillet (illustrated), single-bevel groove, double-bevel groove, single-J groove, double-J groove.

Studding: Distributing of metallic studs along the face of metallic parts to be welded so that the weld cannot pull away from the base metal.

Tack weld: Weld used for assembly purposes only.

Tacking: Making of tack welds.

Tee joint: Joint formed by placing the edges of one metal part, or plate, on the face or surface of another base-metal part in such manner that this surface extends on both sides of the joint (see Fig. 80).

Tensile strength (compressive or shearing strength): Maximum stress developed in the material during test, load being referred to the original cross section.

Test specimen: Prepared section of the structure on which a mechanical test is performed.

Test weld: Weld performed under known conditions and upon which mechanical tests are to be made.

Theoretical throat: See Throat of fillet weld (see Fig. 81).

Thermal stress: Stress produced in a structure or member by differences in temperature or coefficients of expansion.

Thermit crucible: Containing vessel in which the thermit reaction takes place.

Thermit mixture: Mixture of plain thermit and other alloying metals.

Thermit mold: Mold formed around the members to be united to receive the molten thermit metal.

Thermit reaction: Chemical reaction between iron oxide and aluminum that produces a highly superheated liquid iron and aluminum oxide slag.

Thermit welding: Nonpressure- (fusion-) welding process wherein the heat is obtained from liquid steel produced by a thermit reaction and the filler metal is supplied by the steel produced in this reaction.

Throat of fillet weld: Minimum thickness of a weld along a straight line passing through its root. The theoretical throat does not include the reinforcement; the actual throat includes the reinforcement (see Fig. 81).

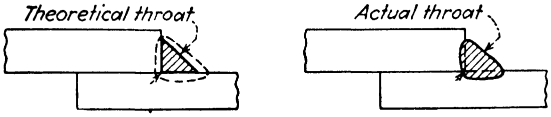


FIG. 81.—Throat of fillet weld.

Tin: Silvery-white, soft, malleable, fusible metal.

Tinning: Coating of a surface with tin or some other molten metal.

Tip (welding tip): That part of a gas torch from which the gas is discharged.

Toe of weld: Intersection of the face of a weld with the base metal (see Fig. 82).

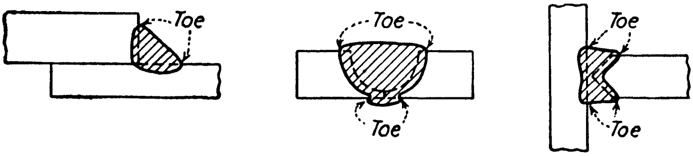


FIG. 82.—Toe of welds.

Torch: Tool or instrument used for gas welding or gas cutting.

Torch head: That part of the torch which holds the tip.

Torch tube: That part of the torch which forms the tube connecting the torch head and handle.

Tough materials: Materials that will withstand heavy shocks or absorb a large amount of energy.

Toughness: Resistance to fracture after permanent deformation has begun.

Types of weld: See Bead, Butt, Fillet, Groove, Plug, Slot weld.

U-groove weld: See Groove weld.

Unaffected zone: That portion of the base metal outside of the heat-affected zone wherein no change in physical properties and/or structure has taken place.

Undercut: Sloughing away of the base metal alongside of the toe of the weld (see Fig. 83).

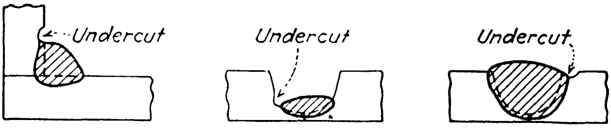


FIG. 83.—Undercut.

Unshielded carbon-arc welding: Carbon-arc-welding process wherein no shielding medium is used.

Unshielded metal-arc welding: Metal-arc-welding process wherein no shielding medium is used.

Upset butt welding: Resistance-butt-welding process in which the parts to be united are brought in contact before the potential is applied across the joint and the heat is derived mainly from the resistance to the flow of current.

Variable-voltage welding source: Source of electric power whose voltage automatically goes down as the current increases, but not in such a manner as to qualify the source as a constant-energy source.

Vee-groove weld: See Groove weld.

Vertical position of welding: See Vertical weld.

Vertical weld (vertical position of welding): Position in which the weld is made in a vertical plane or in a plane inclined at an angle of 60 deg. or less to the vertical, with the line of the weld running vertically.

Volatility: Ease with which substances may be vaporized.

Volt: Unit of electromotive force or pressure. The electromotive force that applied to 1 ohm will produce a current of 1 amp.

Warping: Distortion; pulling out of line or place.

Watt: Unit of power. One joule per sec.

Weaving: Technique of depositing weld metal in which the electrode is oscillated at right angles to the direction of travel (see Fig. 84).

Weld: Localized consolidation of metals by a welding process.

Weld metal: Material of which the weld is formed. It may result from the fusion of the filler metal or base metal, or both.

Weld-metal zone: That part of a weld which has been heated to the molten or plastic state.

Weld penetration: See Penetration.

Weldability: Capacity of a substance to form a strong bond of adherence under pressure or when solidifying from a liquid state.

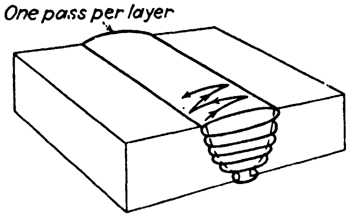


FIG. 84.—Weaving.

Welded joint: Localized union of two or more parts by welding.

Welding ground: See Ground connections.

Welding jig: See Jig.

Welding leads: Conductors furnishing an electrical path between the source of welding power and the electrodes.

Welding operator: Operator of welding equipment, or an operator who makes the weld.

Welding pressure: External force applied in pressure-welding processes to control the current density throughout the weld, or the effects of fusion, or both.

Welding procedure: Detailed methods and practices used in welding a structure.

Welding rod: Filler metal, in wire or rod form, used in the gas-welding process and those arc-welding processes wherein the electrode does not furnish the metal.

Welding sequence: Order of procedure in welding the component parts of a structure.

Welding tip: See Tip.

Welding torch (blowpipe): Device used for mixing and controlling the gases in the gas-welding processes.

Weldment: Assembly whose component parts are joined by welding.

Yield point: Stress at which marked increase in deformation of the specimen occurs without increase in load.

Yield strength: Stress at which a material exhibits a specified limiting permanent set.

Zinc: Bluish-white metal.

CHAPTER IV

A STUDY OF THE DIFFERENT WELDING PROCESSES AND THEIR BASIC PRINCIPLES

As shown in Chart I, all welding processes come under three general classifications: pressure processes, fusion "(nonpressure)" processes, and brazing processes.

The *pressure processes*, as the term implies, are those in which the weld is effected by means of pressure. The *fusion* (nonpressure) *processes*, are those in which the weld is effected without pressure. *Brazing processes* use a nonferrous or alloy filler metal whose melting point is lower than that of the metals or alloys to be welded, but higher than 1000°F.

FORGE WELDING

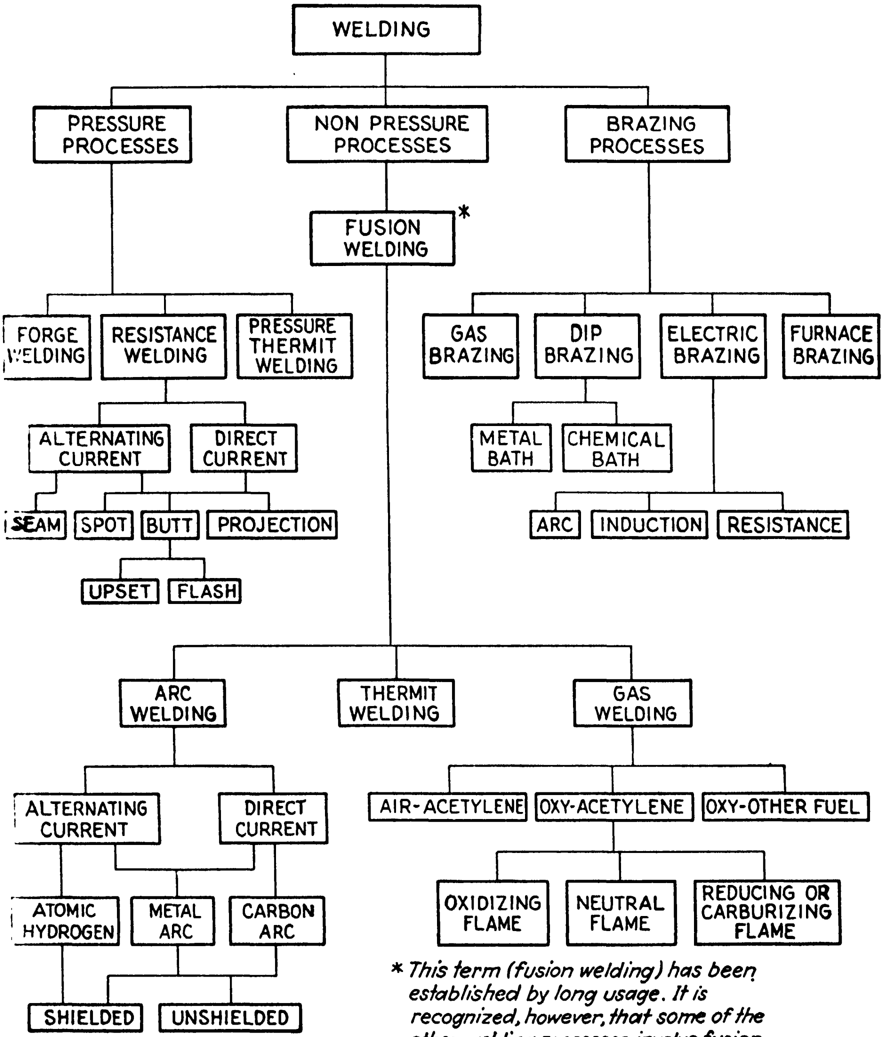
Forge welding, the familiar method used in the blacksmith shop, may well be considered as the original metal-joining process. Thousand of years have passed since the day when man first learned to unite metals by forge welding.

General.—In forge welding, the parts to be welded are heated in a forge or any other appropriate furnace until they become soft and plastic. They are then made to stick together by hand or power hammering or squeezing one against the other.

The quality of the weld depends to a great extent upon the amount of heating the pieces have undergone. If the ends to be joined are not heated enough, they will not stick together; if overheated, the metal becomes burned, is brittle, and has a rough spongy appearance. Also, it is important to secure a uniform temperature throughout the heated ends, or the weld will be defective.

Scale, or oxide of iron, forms on the surface of heated iron when the latter is exposed to the atmosphere, because there is an absorption of oxygen. This scale prevents the formation of a good weld. Therefore, the oxygen in the air blast of the heating furnace should be consumed before it reaches the metal being heated. A thick bed of fuel beneath the work and a not too strong blast will prevent the oxygen from passing through and oxidizing the iron.

A flux is also used to prevent the formation of scale. This substance, usually sand or borax, melts at a temperature below that necessary for welding. Sprinkled upon the surfaces to be joined when they have reached about a yellow heat, the flux melts and covers the surfaces, thus forming a protective coating. When molten, it combines with any oxide that may have formed, lowers its melting point, and therefore helps to dissolve it.



** This term (fusion welding) has been established by long usage. It is recognized, however, that some of the other welding processes involve fusion.*

Chart I.—Master chart of welding processes. (*Courtesy of American Welding Society.*)

The fuels used for heating iron and steel preparatory to forging or welding are mainly coke, coal, charcoal, oil, and gas, the coke fire being the most widely used. It is important that the fuels be low in sulphur, for the latter makes the steel brittle while hot, or, to use the common term, "hot-short." The welding itself can be accomplished by the hand-forging practice or by means of a forging machine.

FIG. 85.—A forge shop in ancient times.

Types of Weld.—The ordinary welds made by hand are the scarf weld, lap weld, butt weld, cleft weld, and jump weld (see Fig. 86). The joint surfaces, in most instances, are rounded or crowned slightly, so that, when brought together, they will unite in the center first and thus force out any slag or dirt that may have stuck upon them. In machine forge welding, three types of weld are used: the lap weld, pin weld, and butt weld (see Fig. 87).

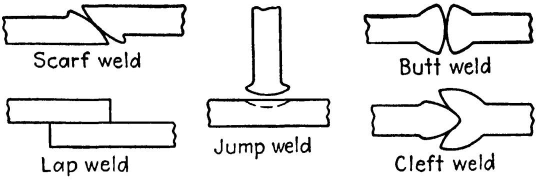


FIG. 86.—Different types of forge welds made by hand.

The forge-welding process is not used widely as a production or manufacturing tool because it is obviously too slow and too costly, even with the latest improvements brought about by the development of heating furnaces and power hammers. Most of its present use is in railroad shops and in country blacksmith shops.

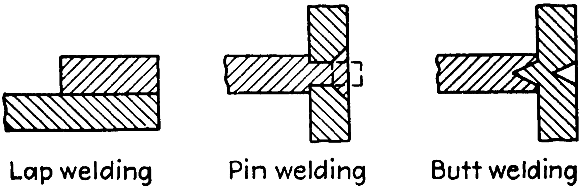


FIG. 87.—Different types of forge welds made by machine.

ELECTRIC-RESISTANCE WELDING

The communication of heat by means of an electric resistance, as made use of in the Thomson process, is almost as old as the procedure of arc welding. It was developed by Elihu Thomson and brought to public notice for the first time in 1886.

General.—The fundamental principle of the electric-resistance-welding process resembles that of forge welding. In the latter process the workpieces are heated in a forge and then hammered together. In resistance welding, the workpieces are heated to a plastic state at a given junction by passing a relatively high current across the joint. They are then pressed together between the contacting terminals.

The welder consists mainly of a single-phase transformer having a secondary of one or two turns (see Fig. 88). A low voltage is required

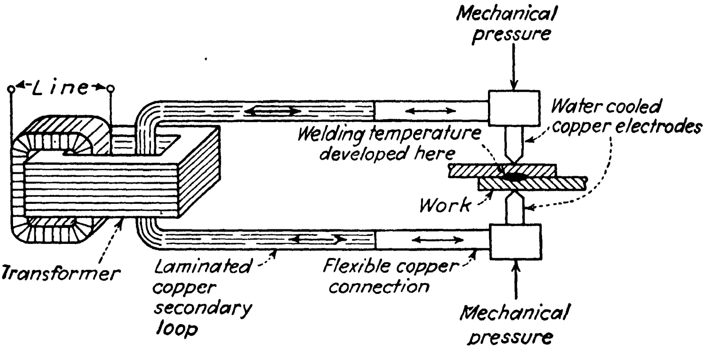

Mechanical pressure
Line
Water cooled copper electrodes
Welding temperature developed here
Work
Transformer
Laminated copper secondary loop
Flexible copper connection
Mechanical pressure

Fig. 88.—Typical circuit of a resistance welder.

between the terminals, and the amount of current needed is dependent only upon the size of the pieces to be handled. A heavy frame, built about the transformer, supports not only the clamping jaws to handle the work but also the mechanical devices used to regulate the heat and the pressure. The electric current is carried to the work by heavy copper conductors, and the resistance to the flow of the current is thus concentrated in the work. This resistance causes the work to become heated enough to reach a "white heat" and to become plastic. The weld is then formed by cutting off the current and applying pressure to these plastic sections.

The union is as strong as any part of the pieces that have thus been joined. An outstanding feature of the process is that the heat is generated principally at the center of the parts being welded and in line with the points of contact (see Fig. 89).

Resistance welding differs from other forms of welding in that there is no introduction of any foreign material into the weld; the welding heat is definitely localized at the desired point, with resulting control of the extent of fusion; there is a high rate of production of welds; it easily unites difficult shapes which could not otherwise be easily joined, as in the case of fine wires and very light sheets; ferrous and nonferrous alloys are readily welded; and even totally different materials, as copper and steel, can be welded together. It facilitates the application of automatic operation, for the equipment can be set up to give the desired results; and there is little skill required on the part of the operator. Also, all welds thus made have approximately the same characteristics.

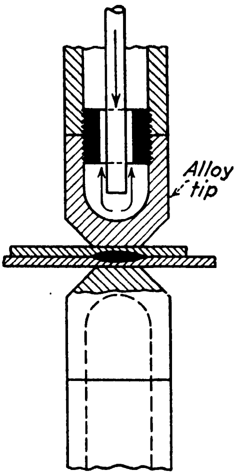


FIG. 89.—Setup of electrodes and work for spot welding.

Electric-resistance welding should be used only for duplicate or production work. One machine is usually designed for handling pieces of the same metal and for making joints of similar design. The economy of the process depends on the volume of duplicate operations that can be performed with it.

To make a good weld, the correct heat must be obtained, the heat must be localized at the desired spot, and the proper forging pressure must be applied at the proper spot at the proper time. Thus, the following factors must be taken into consideration in the making of a resistance weld: pressure; current; resistance of the material and contact surfaces; the time, or duration, of the flow of the current; and the area of contact of the electrodes or pieces in the welder. The last four produce and determine the heat. The pressure is important for two reasons: It has an important influence upon the resistance of the surface contacts between the parts and the electrodes. Also, it determines the welding temperature of some alloys. The greater the pressure applied, the less the resistance of contact. Cleanliness of the surfaces is also important. If

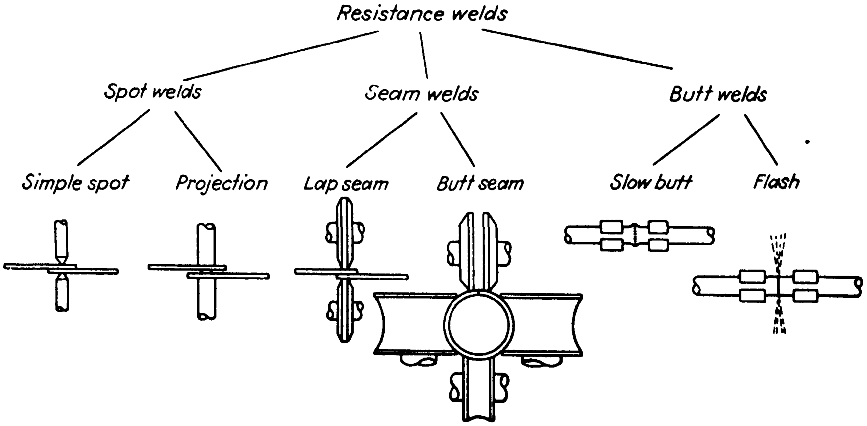


FIG. 90.—Resistance welds.

the surfaces are really clean and if the pressure is great enough, some metals and alloys will weld at a comparatively low temperature.

Subdivisions.—The subdivisions of the resistance-welding process are determined by the location of the weld and the method of making the weld. They are principally spot, butt, and seam welding.

In *spot welding* the metals are welded or fused at a spot. As it is usually applied in the joining of light sheets, a large current, at a low voltage, is discharged through two or more pieces of metal. The discharge of current is followed with sufficient pressure to unite the molecules of the workpieces. The current is cut off before the mechanical pressure is released so as to prevent burning the contacting electrodes.

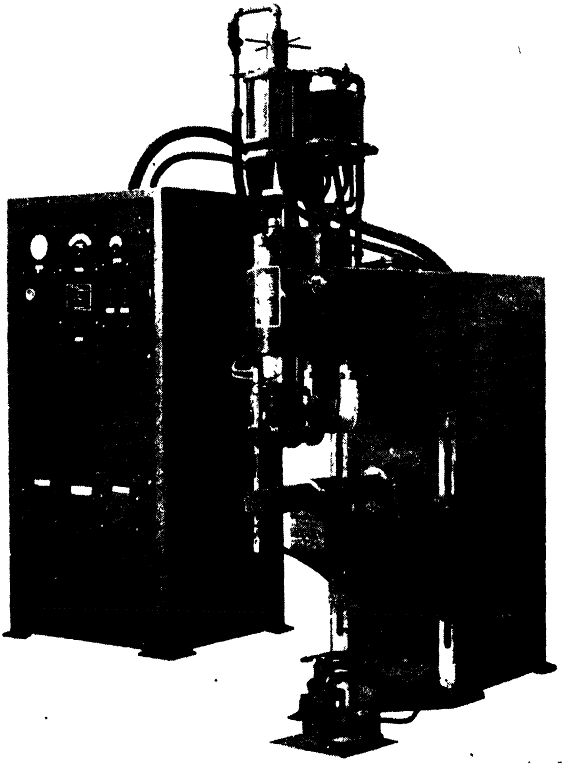


FIG. 91.—Spot welder. (*Courtesy of The Taylor-Winfield Corporation.*)

Simple spot welds are obtained when small contact areas on the electrodes are used. If, prior to welding, one or more points, or projections, are raised above the plane surfaces of the parts to be welded and if these parts are placed between electrodes having large contact areas, then the resulting weld is called a *projection spot weld.* *Ridge welding* is obtained if ridges are raised instead of point projections. The ridges of one part should cross the ridges on the other part or parts to be welded.

Butt welding is obtained when pieces having practically the same cross section are welded end to end. The weld is made by heating the entire areas of the butted surfaces to a fusing temperature and applying pressure. The pieces are held in alignment by suitable clamping electrodes, or jaws. If the pressure is applied and persists while the parts are being heated, the welds are characterized by large upsets or swellings at the fused section and are known as *slow butt welds*. If, while the power is applied to the clamping electrodes, the surfaces are brought close to one another so as to cause a spark, or flash, to jump across the gap until the proper fusion temperature is obtained and if the forging pressure is then suddenly applied, a *flash weld* results. It is marked by small upsets.

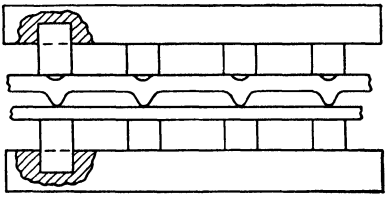


FIG. 92.—Typical setup for projection welding (projections on one workpiece only).

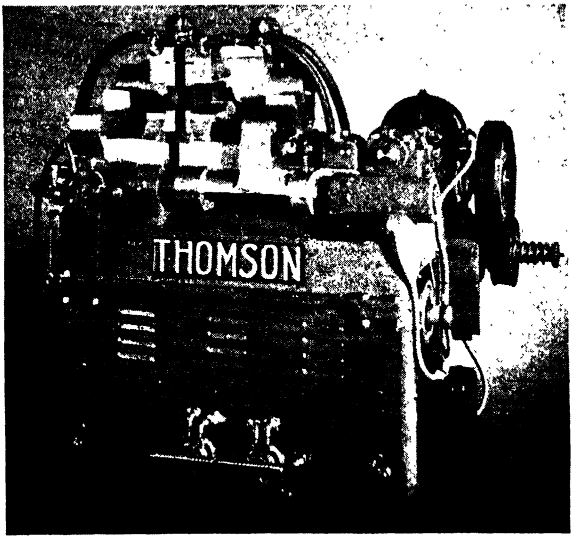


FIG. 93.—Flash welder. (*Courtesy of Thomson-Gibb Electric Welding Company*)

The *seam weld* is similar to a spot weld, except that circular rotating electrode wheels, contacting the opposite faces under pressure, are used to produce the effect of a seam. The weld may be continuous if the current is passed at short enough intervals, or it may consist of a series of spot welds if the current is passed at long enough intervals. Both lap and butt seam welds can be thus made (see Fig. 90).

With the exception of seam welding, direct and alternating current can be used for all kinds of resistance welding. Alternating current only can be used for seam welding.

The initial cost of the equipment is often pointed out as a decided disadvantage of the process, but resistance welding was developed and should be used for mass production, thus justifying the high initial cost of investment. The operating cost and the labor cost are remarkably low.

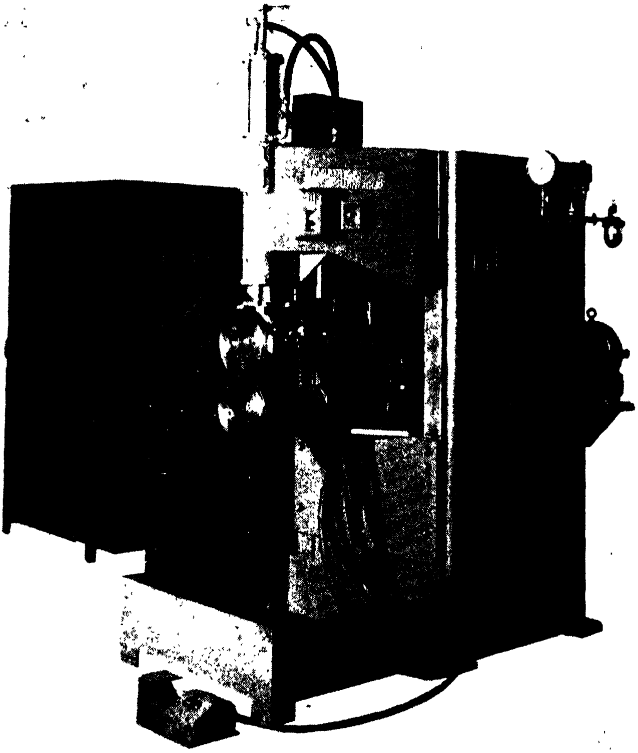


FIG. 94.—Seam welder. (*Courtesy of The Taylor-Winfield Corporation.*)

THERMIT WELDING[1]

The thermit process was among the first of the new metal-joining methods to be developed and perfected.

In 1894, C. Vautin discovered that by mixing finely powdered aluminum with metallic oxides, sulphides, and chlorides and by then igniting the mixture a very high temperature of little less than 3000°C. resulted.

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[1] A good many of the data and material for this section have been condensed from Chap. XV of the "Welding Handbook" of the A.W.S.

At the same time, the metal was readily reduced and remained in a very high degree of purity.

Dr. Hans Goldschmidt, a German scientist, later made practical use of the reaction and was able to weld two iron bars by means of molten iron produced by what is now known as the "thermit process." The reaction resulted in masses of molten metal and aluminum oxide slag, which separated of their own accord because of the wide differences in weight. Also, it was noted that the reaction would proceed in most cases at a very rapid rate. For instance, it was possible to produce any quantity up to a ton or more of material in a single reaction lasting about 30 sec.

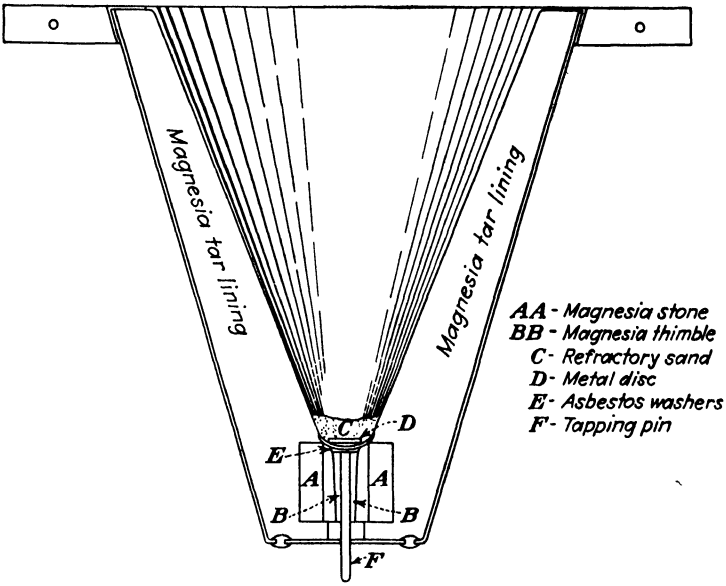


FIG. 95.—Thermit automatic crucible. (*Courtesy of Metal and Thermit Corporation.*)

Dr. Goldschmidt was granted an initial patent in 1897, but it was not until a year or so later that the first attempts were made to utilize the high temperatures of the reaction as a source of heat for welding.

General.—Thermit welding is primarily a fusion-welding process in which the weld is effected by pouring superheated liquid thermit steel around the parts to be united.

The thermit is a mixture consisting principally of finely divided aluminum and iron oxide. The proportions are approximately three parts of oxide, or magnetic iron scale, to one of aluminum. The mixture, placed in a refractory-lined crucible, is ignited with the aid of a highly inflammable powder composed largely of barium peroxide. The reaction according to the chemical representation is as follows:

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3$$

During the reaction, then, the oxygen leaves the iron oxide and combines with the aluminum which has a strong affinity for it, producing aluminum oxide, or slag, and superheated thermit steel.

Besides aluminum and iron oxide, other materials are added to the mixture to control the quality and properties of the resultant weld metal. The average analysis of thermit steel employed for welding is

	Per Cent
Carbon	0.05–0.10
Manganese	0.08–0.10
Silicon	0.09–0.20
Sulphur	0.03–0.04
Phosphorus	0.04–0.05
Aluminum	0.07–0.18

A thermit steel of the above composition has physical properties resembling those of forged steel.

The reaction is nonexplosive and requires, as seen previously, about 30 sec. to complete. The handling and storing of the mixture are not dangerous, for an initial temperature of 1300°C. or 2372°F. is needed for ignition. The thermit mixture should be kept dry, for if it becomes wet or damp, it cannot be restored to its original state.

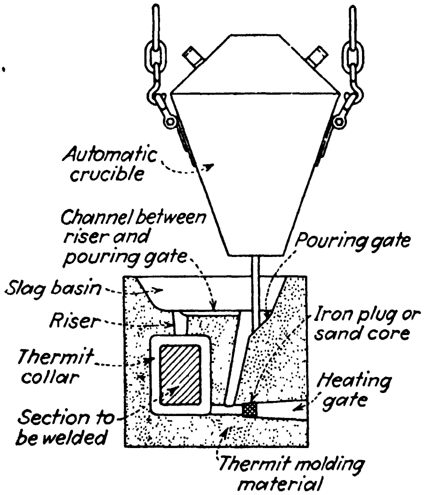
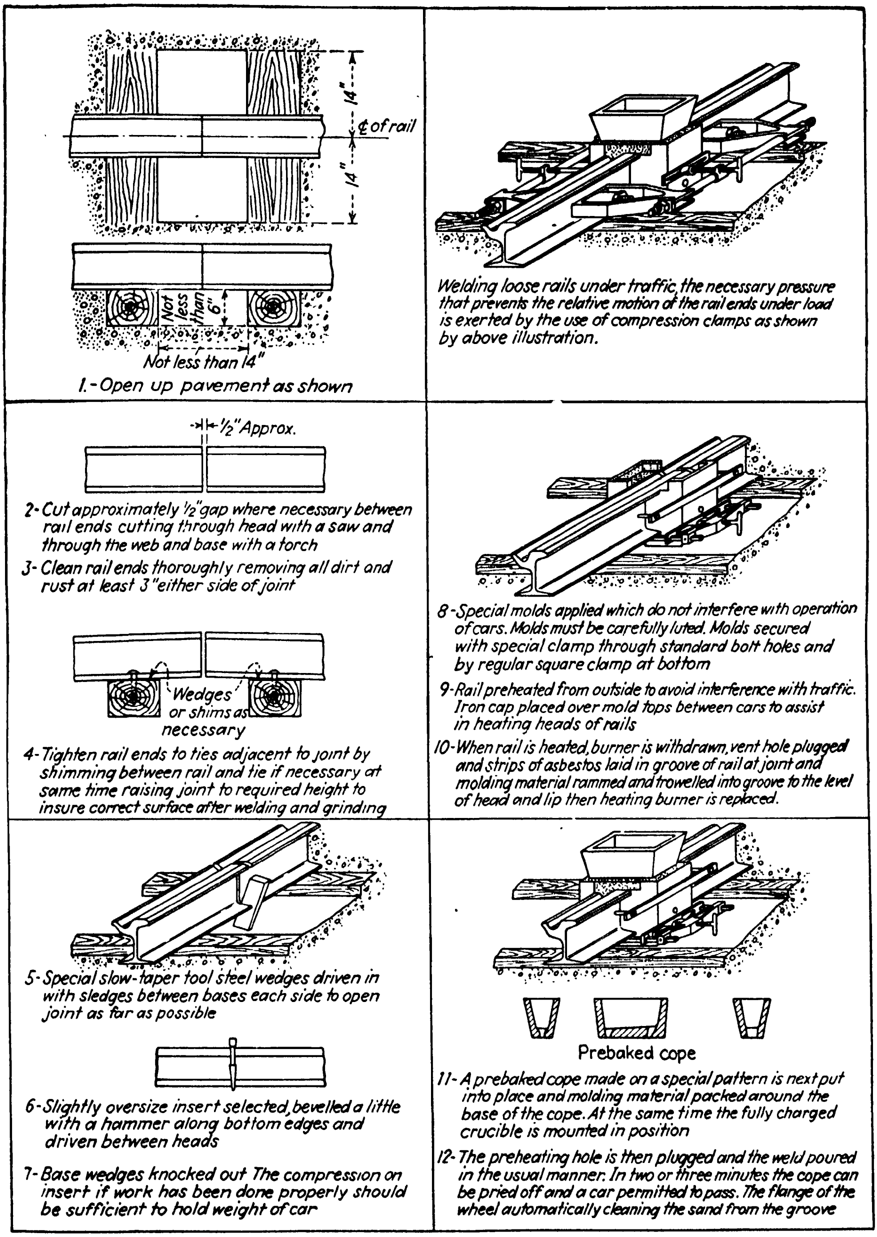


FIG. 96.—Materials needed in the making of a thermit weld. (*Courtesy of American Welding Society.*)

Applications of Thermit Welding.—The very intense heat given off by the reaction measures about 4880°F. or 2690°C. After the reaction, the steel settles at the bottom of the crucible and is drawn off at a temperature of about 4172°F. or 2300°C. into a mold previously prepared about the parts to be welded. The thermit steel, which is therefore about twice as hot as ordinary molten steel, fuses and amalgamates with the parts inside the mold, forming a single homogeneous section. The parts are preheated before the liquid metal is poured into the mold in order to prevent the chilling of the steel.

The above is only one of the two distinct methods by which a thermit weld may be made. In the other method, only the heat of the slag and the heat of the metal are utilized. This is known as the *plastic method* or *pressure thermit process*. For instance, in the welding of pipes (see



1.-Open up pavement as shown

2- Cut approximately ½" gap where necessary between rail ends cutting through head with a saw and through the web and base with a torch

3- Clean rail ends thoroughly removing all dirt and rust at least 3" either side of joint

4- Tighten rail ends to ties adjacent to joint by shimming between rail and tie if necessary at same time raising joint to required height to insure correct surface after welding and grinding

5- Special slow-taper tool steel wedges driven in with sledges between bases each side to open joint as far as possible

6- Slightly oversize insert selected, bevelled a little with a hammer along bottom edges and driven between heads

7- Base wedges knocked out The compression on insert if work has been done properly should be sufficient to hold weight of car

Welding loose rails under traffic, the necessary pressure that prevents the relative motion of the rail ends under load is exerted by the use of compression clamps as shown by above illustration.

8-Special molds applied which do not interfere with operation of cars. Molds must be carefully luted. Molds secured with special clamp through standard bolt holes and by regular square clamp at bottom

9-Rail preheated from outside to avoid interference with traffic. Iron cap placed over mold tops between cars to assist in heating heads of rails

10-When rail is heated, burner is withdrawn, vent hole plugged and strips of asbestos laid in groove of rail at joint and molding material rammed and trowelled into groove to the level of head and lip then heating burner is replaced.

11- A prebaked cope made on a special pattern is next put into place and molding material packed around the base of the cope. At the same time the fully charged crucible is mounted in position

12- The preheating hole is then plugged and the weld poured in the usual manner. In two or three minutes the cope can be pried off and a car permitted to pass. The flange of the wheel automatically cleaning the sand from the groove

FIG. 97.—**Steps in making a thermit rail weld under traffic.** (*Courtesy of American Welding Society.*)

Fig. 98), special clamps are attached to the pipe with the mold. When the products of the reaction are poured, the slag flows into the mold and coats the outside of the pipe and the inside of the mold. The slag is followed by the steel which displaces in the bottom part but does not remove the slag coatings. Then the heat of the superheated steel brings the pipe to welding temperature but does not fuse with it. The clamps are then drawn up to force the ends of the pipes together and to provide a pressure butt weld.

Special containers and specially prepared mixtures are needed in the thermit process, plus molding materials, preheating equipment, and various accessories.

The main steps of the welding operations are as follows: The sections to be welded should be cleaned; enough metal should be removed at the joint to provide for a free flow of thermit steel; the members should be aligned, and a mold made around them to retain the steel; the members should be preheated by means of a gasoline or kerosene preheater or torch; the thermit mixture in the crucible should be ignited, and the molten steel should be tapped into the mold.

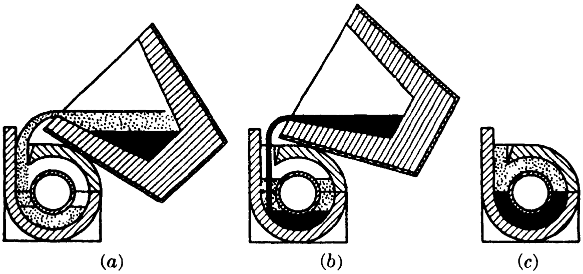


Fig. 98.—Thermit pipe-welding operation: (*a*) Slag flowing into mold and coating outside of pipe and inside of mold. (*b*) Slag in mold and steel following, displacing slag in bottom part. (*c*) Both slag and steel in mold but steel separated from pipe and mold by film of slag. (*Courtesy of American Welding Society.*)

Thermit welding is especially applicable to the welding of large sections and has a certain usefulness in the repair of heavy parts, such as locomotive frames, rudder and stempost of ships, crankshafts, railroad tracks, spokes of driving wheels, broken motor casings, and connecting rods. The process is also used to a great extent in the welding of pipes.

One of the great advantages of the process is that broken parts can usually be welded in place; but because of the necessity for molds and dams, its application is limited.

ELECTRIC-ARC WELDING

The transformation of electrical energy into heat in the form of an electric arc and the application of the heat thus liberated to fuse metals to be welded are of comparatively recent date.

It was in 1881 that De Meritens first made use of arc welding for uniting the parts of storage-battery plates. In his experiment, the workpiece, properly supported, was connected with the positive pole of a source of current capable of maintaining an electric arc. A carbon rod was connected to the other pole and so set up that it could be controlled by the operator to strike and maintain the arc. The heat of the arc, partly communicated to the storage-battery plate and partly lost in the surrounding air, fused the metallic lead of the plate, and the various constituent parts were united.

The method developed by De Meritens was modified by others, among whom are outstanding Bernardos and Olszewski, Slavienoff, and Coffin.

In their process, Bernardos and Olszewski made the work the negative pole of a d.c. circuit, attached a carbon rod to the positive pole, and drew an arc between the two, the carbon rod being manipulated with an insulating handle. With this setup, it was soon realized that particles of carbon might be easily introduced into the molten metal, making it hard and brittle to the extent of cracking or becoming unworkable.

Slavienoff modified this arc-welding process by replacing the carbon rod with a metallic electrode. He found that, upon striking an arc, the metallic electrode gradually melted and furnished fused drops of metal.

The patent for the carbon-electrode process was allowed to Bernardos in 1887, but the patent for the metallic-electrode process was allowed to Coffin in 1889.

Subdivisions.—Metallic-arc and carbon-arc welding are the two most important arc-welding methods and will be discussed at great length in later sections. Atomic-hydrogen-arc welding also comes under the heading of arc welding. A discussion of this process follows at the end of this section.

Curious but Interesting Operations Resembling Arc Methods.—A sort of electric blowpipe was proposed in 1874 by Werdermann. The method consisted in using the flame gases of an electric arc deflected by an air jet or the like. The proposal was later revived by Zerener, with the suggestion that the arc be deflected between the usual carbon electrodes by a magnetic field.

These processes could not be truly called "electric," for the metal to be heated took no part in the conduction of current. Rather, the heat was communicated by the gases of the arc and, to a very small extent, by the radiation from the hot electrodes.

A rather wasteful but nevertheless interesting proposition was made in regard to heating metal pieces before they were brought under the hammer for forging or welding. The method consisted in plunging the end of the metal bar into an electrolytic bath while connected with the negative pole of a circuit having a potential of 100 to 150 volts, such as a lighting circuit. Either the positive pole might be connected to a metal plate immersed in the electrolyte, or the containing vessel itself if made of metal might be so connected. The electrolyte, that is, a solution capable of conducting current, might be a solution of sodium or sodium carbonate. The immersed part of the metal bar, acting as a cathode of limited surface, soon glowed luminously and gas bubbles arose from its surface. In other words, it heated rapidly and has even been known to melt. Hoho and Lagrange, who originally made this action known, offered as an explanation the probability of an arc forming between the surface of the immersed metal and the adjacent liquid layer. The resulting intense heat was partly communicated to the bar, but most of it was carried off in the liquid bath and thus wasted.

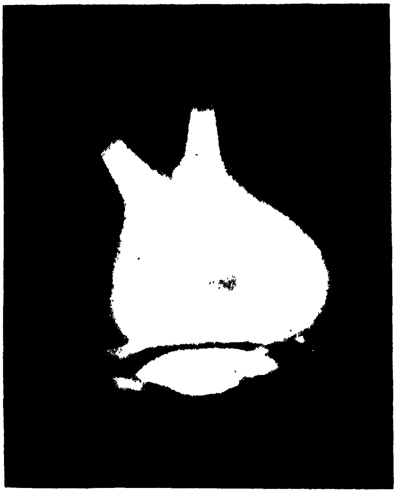


FIG. 99.—Atomic - hydrogen - arc flame. (*Courtesy of General Electric Company.*)

ATOMIC-HYDROGEN-ARC WELDING

In the atomic-hydrogen-arc-welding process, an arc is maintained between two tungsten electrodes while a stream of hydrogen gas is passed through the arc and around the electrodes. The stream, or flame, assumes a fan shape and produces a sharp singing noise (see Fig. 99).

General.—Molecular hydrogen, or hydrogen in its normal state as distinguished from atomic hydrogen, is a diatomic gas. That is, each molecule consists of two atoms. When hydrogen is broken down into the atomic form, it is very active and has a great tendency to recombine to form molecular hydrogen. This is exactly what happens in the atomic-hydrogen process. When the molecular hydrogen passes through the arc, much of it is changed into the atomic state and thus absorbs a considerable amount of energy. In escaping the arc stream, these atoms recombine into molecules again at the outer edge of the arc fan, and the extra energy is released as heat. This extra heat, added to the intense heat of the arc itself, produces a temperature that is somewhat higher than either the ordinary arc or gas flame. The theoretical temperature of the atomic-hydrogen flame has been found to be 7254°F.; however, heat absorption due to the formation of atomic hydrogen reduces this to 5342°F. Since all this heat is concentrated in the relatively small volume of the arc fan, good instant transfer of heat to the work is obtained. Also, the arc is independent of the work and can be moved instantly at will.

One of the other principal benefits of this process is that the hydrogen excludes all oxygen and other gases which might combine with the molten metal to form oxides and other impurities. What is more, it also removes oxides from the surface of the work. Thus, it is capable of producing unusually smooth, uniform, strong, and ductile welds.

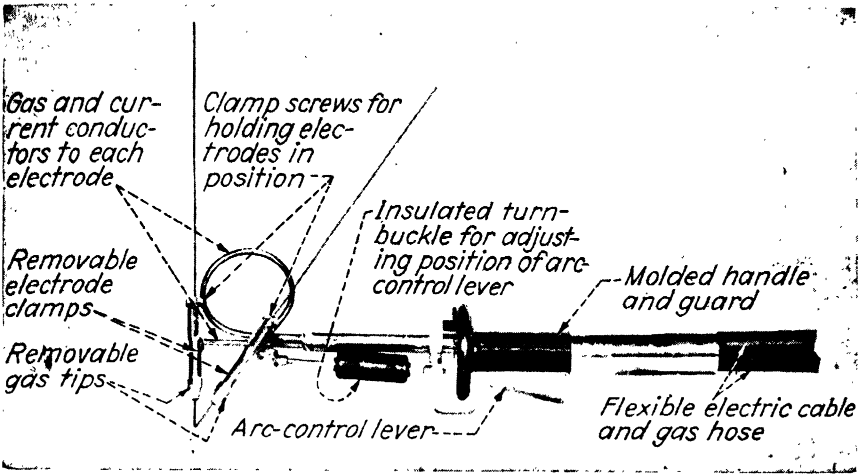

Gas and current conductors to each electrode
Clamp screws for holding electrodes in position
Insulated turnbuckle for adjusting position of arc-control lever
Removable electrode clamps
Molded handle and guard
Removable gas tips
Arc-control lever
Flexible electric cable and gas hose

FIG. 100.—Atomic-hydrogen-arc welding torch. (*Courtesy of General Electric Company.*)

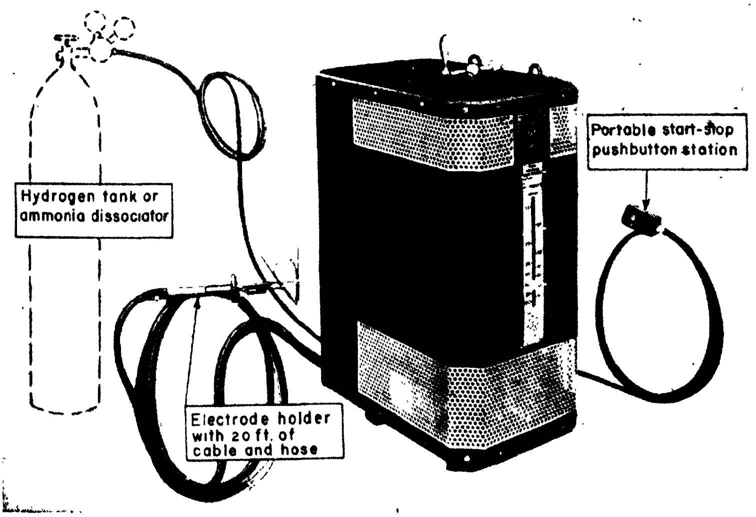

Hydrogen tank or ammonia dissociator
Portable start-stop pushbutton station
Electrode holder with 20 ft. of cable and hose

FIG. 101.—Setup of equipment for atomic-hydrogen-arc welding. (*Courtesy of General Electric Company.*)

Equipment.—The necessary equipment includes a transformer, a power-control unit, an electrode holder, tungsten electrodes, and a source of hydrogen. A typical setup of the equipment is shown in Figs. 100 and 101.

With the exception of electrode holders, the accessories ordinarily required with a manually operated atomic-hydrogen-arc-welding installation are the same as those required for any other arc-welding work.

Operation of Equipment and Technique.—The operation of an atomic-hydrogen arc-welding equipment is only slightly different from that of any other type of arc welder. With reference to the General Electric equipment shown in Fig. 101, the following instructions will be found to apply.

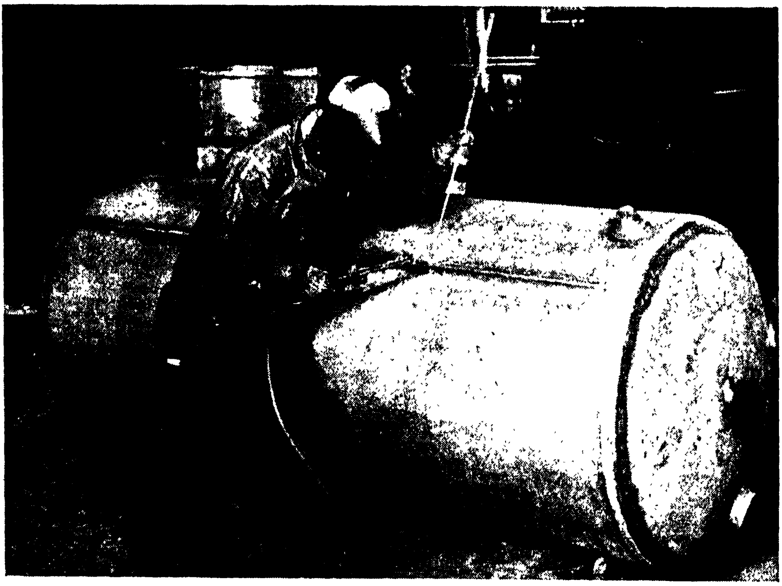


Fig. 102.—Monel metal gasoline storage tank fabricated by atomic-hydrogen-arc welding. (*Courtesy of General Electric Company.*)

In order to start the arc (on the assumption that the equipment is properly installed and adjusted according to instructions) the operator should grasp the electrode holder and pull the trigger until the electrodes are separated. He should then press the "Start" button while he allows the electrodes to come together momentarily to strike the arc, after which the electrodes should be immediately separated to about $\frac{1}{16}$ in. This operation results in the igniting of the hydrogen as well as in the starting of the arc. The flow of hydrogen is controlled automatically. The "Start" button should be released as soon as the arc is established.

The operator should then adjust the current, by means of the handwheel on top of the unit, to suit the thickness of the material being welded. The amount of current flowing is indicated on the Vernier scale.

The electrodes used should be large enough, of course, to accommodate the current required without excessive consumption of the tungsten.

The arc can be stopped by depressing the "Stop" button or by increasing the gap between the electrodes until the arc breaks.

Since the arc is established between two electrodes, the work does not form a part of the electrical circuit and, therefore, does not need to be grounded. A filler rod may or may not be used, depending on whether the desired joint requires the addition of metal. The tungsten electrodes do not enter into the weld, although they are very slowly evaporated by the intense heat of the arc.

Viewed through a welding glass, the arc stream is seen to have a very definite circular outline, as illustrated in Fig. 99. The greatest concentration of atomic hydrogen (and therefore heat) occurs at the boundary of the arc stream, the edge of which should just touch the surface to be welded. The amount of heat available for welding depends on both the welding current and the size of the arc fan.

The manipulation of the electrode holder is somewhat similar to that of the manipulation of a gas torch. Used mainly for edge welding of light-gauge metals, the flame is played over the edges to be joined, thus fusing them together. A filler rod may be used with the heavier gauges if necessary.

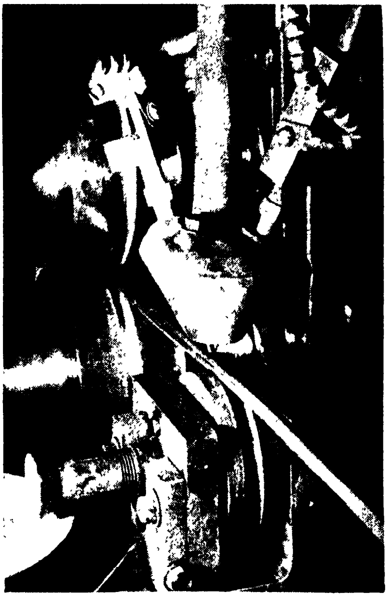


FIG. 103.—Automatic atomic-hydrogen-arc welding head used to fabricate a special heat-resisting alloy tubing. (*Courtesy of General Electric Company.*)

Automatic Operation.—Automatic welding by machine operation can be successfully performed by the atomic-hydrogen-arc-welding process both on straight and circular seams, but it should be used only where the volume of work is sufficient to warrant the investment required.

In automatic welding, an atomic-hydrogen-arc-welding head is used in place of the hand-operated electrode holder. In addition, a welding unit of proper size is required, as well as a thyratron panel for automatically controlling the arc, an operator's control station, and either a travel carriage for moving the welding head over the work or a suitable travel mechanism for moving the work under the head (see Fig. 103).

Applications.—Atomic-hydrogen-arc welding may be used where fusion welding is required on special ferrous alloys, such as chrome, nickel, and molybdenum steels, and on nonferrous metals and alloys, such as aluminum, duralumin, nickel, Monel, copper, brass, and bronze. It is also used for hard-surfacing purposes and for the repairing of tools and dies. The operating costs are usually higher than for other processes; and, for this reason, it is not competitive in certain fields. It is of maximum practical value on those applications which cannot be handled so successfully by ordinary methods.

GAS WELDING—THE OXYACETYLENE FLAME AND ITS APPLICATION[1]

The use of the blowpipe in metalworking is by no means a new thing. A crude form of blowpipe was used by the ancient Egyptians, Greeks, and Romans to work precious metals as well as metals of low melting point, such as lead. The flame was derived from alcohol and similar fluids. But the discovery of gases yielding high temperatures was really what fostered the present development of the blowpipe for welding.

Although acetylene was discovered as early as 1836, it was not widely used, except in laboratories, until 1892, when a method of producing calcium carbide in large quantities was discovered. The flame characteristics were noticed as early as 1895, but it was not until some years later, when suitable and satisfactory equipment for producing and controlling the flame was developed, that the flame was used for welding on a commercial basis.

The year 1903 marks the beginning of the oxyacetylene process for general use in welding and cutting.

General.—Gas welding is a fusion-welding process in which the required heat is supplied by a high-temperature flame obtained by a mixture of two gases. The two gases are mixed in proper proportions in a welding blowpipe or torch which is designed so that the operator has complete control of the welding flame.

Common mixtures of gases are oxygen and acetylene, air and acetylene, oxygen and hydrogen, and oxygen and any other combustible gas. The oxygen-acetylene mixture is almost universally used and has a prominent place in the welding industry.

Oxygen and Acetylene—Their Properties and Production.—*Oxygen* is a colorless, tasteless, and odorless gas. Its main characteristic, of course, is its ability to support and intensify combustion. Pure oxygen is a very active substance even at ordinary pressures. This activity is increased still more when the oxygen is at high pressure, and in this condition it may combine violently with oil or grease even at ordinary temperatures.

Oxygen for welding purposes is produced mainly from liquid air. Air consists of about one-fifth oxygen, the remainder being nitrogen, with a small percentage of rarer gases such as argon, neon, and helium. Air can be liquefied and then separated into its component parts by a carefully controlled process of rectification, which takes advantage of the fact that liquid nitrogen boils at a lower temperature than liquid oxygen. The oxygen is separated from the mixture and delivered to a storage holder. From there, it is compressed in cylinders for shipment.

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[1] A good deal of the data and material included here has been condensed from literature issued by the International Acetylene Association (I.A.A.).

Acetylene is a colorless, combustible gas and has a characteristic odor. It has a compound of carbon and hydrogen, having the chemical formula C_2H_2.

Acetylene forms explosive mixtures with air and oxygen. Regulations and laws forbid the generation, compression, or use of fuel acetylene at pressures above 15 lb. per sq. in., for higher pressure may cause explosions under certain conditions.

As mentioned previously, acetylene is produced by the chemical reaction between water and calcium carbide, CaC_2. When a piece of calcium carbide is dropped into water, bubbles of a gas that is acetylene gas will rise. The reaction is as follows:

CaC_2	+	$2H_2O$	=	C_2H_2	+	$Ca(OH)_2$
Calcium carbide		Water		Acetylene		Hydrated lime

The calcium carbide is a gray stonelike substance produced by smelting lime and coke in an electric furnace. The hydrated lime is the whitish residue that remains in the water after the action has stopped.

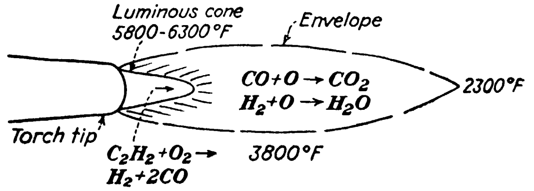


FIG. 104.—The oxyacetylene flame: its related reactions and temperatures.

The Oxyacetylene Flame.—The oxyacetylene flame, like all other flames, is a phenomenon produced at the surface where two gases meet and undergo combustion with the evolution of heat and, more or less, light. With commercially pure oxygen and acetylene, however, the hottest known flame may be produced, its estimated temperature being in the neighborhood of 6000°F.

The chemical reaction for the complete combustion of oxygen and acetylene is as follows:

$2C_2H_2$	+	$5O_2$	=	$4CO_2$	+	$2H_2O$
Acetylene		Oxygen		Carbon dioxide		Water vapor

This means that two volumes of acetylene and five volumes of oxygen combine, or react, to produce four volumes of carbon dioxide and two volumes of water vapor. In other words, for complete combustion of acetylene the ratio of oxygen to acetylene is 2½ to 1.

The flame temperature produced is dependent upon the relative proportion of these two gases. Since the flame temperature alone, however, is not the only factor in the commercial use of the oxyacetylene flame, varying ratios have been found most suitable for different purposes. For oxyacetylene welding and heating, the most suitable mixture is generally obtained by employing approximately equal proportions of oxygen and acetylene through the blowpipe. This mixture when burned at the tip of a properly designed torch or blowpipe produces what is known as a "neutral" flame because its action is neutral in effect, that is, neither oxidizing nor carburizing. In the combustion of this mixture, there is a double chemical action, as follows:

FIG. 105.—Neutral oxyacetylene flame. (*Courtesy of The Linde Air Products Company.*)

$$\underset{\text{Acetylene}}{C_2H_2} + \underset{\text{Oxygen}}{O_2} = \underset{\text{Carbon monoxide}}{2CO} + \underset{\text{Hydrogen}}{H_2}$$

This means that one volume of acetylene for one volume of oxygen will produce two volumes of carbon monoxide plus one volume of hydrogen. This reaction takes place at the inner cone of the flame where the highest temperature is developed (see Fig. 104). The carbon monoxide and hydrogen are then burned to carbon dioxide and water vapor, as follows:

$$\underset{\text{Carbon monoxide}}{2CO} + \underset{\text{Oxygen}}{O_2} = \underset{\text{Carbon dioxide}}{2CO_2}$$

$$\underset{\text{Hydrogen}}{2H_2} + \underset{\text{Oxygen}}{O_2} = \underset{\text{Water vapor}}{2H_2O}$$

The oxygen required for the burning of carbon monoxide and hydrogen to carbon dioxide and water vapor is provided by the atmosphere. It can be seen from the above that in the neutral oxyacetylene flame 1 part of oxygen is provided from the torch or blowpipe and 1½ parts of oxygen is provided from the atmosphere in order to complete the combustion of 1 part of acetylene.

The neutral flame is clearly indicated by a well-defined white inner cone at the torch tip (see Fig. 105). Adjustments, furthermore, of the valves on the blowpipe provide an easy means of obtaining this flame, for a carburizing flame is indicated by a secondary luminous cone surrounding the inner cone and extending into the outer envelope (see Fig. 106). An oxidizing flame, on the other hand, is indicated by a shortening and pointing of the inner cone and a reduction in its luminosity (see Fig. 107).

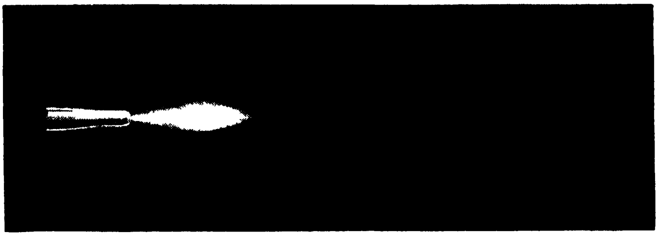


FIG. 106.—Excess acetylene or reducing oxyacetylene flame. (*Courtesy of The Linde Air Products Company.*)

Although the neutral flame is most generally used for all heating and welding operations, there are special uses for both the carburizing flame and the oxidizing flame. With the carburizing, or excess-acetylene, flame, free carbon is deposited in a very fine form. Use of this free carbon in welding has been taken advantage of in welding steel, for a thin layer of highly carburizing iron is formed which will melt at a lower temperature than the iron itself. The presence of this mixture, therefore, is conducive to fusion and shortens the period of heating so that the rate of welding is faster than with the neutral flame. As the flame is made increasingly carburizing, however, the flame temperature drops and the amount of carbon deposited increases. For this reason in welding only small amounts of excess acetylene are used.

FIG. 107.—Oxidizing oxyacetylene flame. (*Courtesy of The Linde Air Products Company.*)

The oxidizing, or excess-oxygen, flame is used where the maximum flame temperature is desired and where the oxidizing effect is beneficial or not detrimental. An oxidizing flame is, therefore, often used in the preheating flame for oxyacetylene cutting operations. In the welding of nonferrous metals, particularly brasses and bronzes, it is desirable to oxidize the impurities which, with some oxidized zinc, when fluxed to the surface form a coating over the weld, and the oxidizing flame is therefore generally used for this purpose.

The Use of the Oxyacetylene Flame.—The use of the oxyacetylene flame is of course predicated upon the fact that it provides a means of securing an intense and highly localized heat when burned through a properly designed blowpipe or torch.

The principal uses made of the flame have been in fusion welding and in conjunction with a separate stream of oxygen in oxyacetylene cutting. Other general uses, however, include bronze welding, soldering, heating, heat-treating, and surfacing.

Oxyacetylene Welding.—Oxyacetylene welding is a form of fusion welding wherein the heat required is supplied by the oxyacetylene flame. Usually, in fusion welding a filler metal is added in the form of a welding rod to form the welded joint, although joints in some instances are formed in oxyacetylene welding merely by fusing together the parts to be joined without the addition of the welding rod. Flux is employed in the welding of some metals as a means of floating out impurities or aiding in obtaining a satisfactory bond.

The oxyacetylene process offers a distinct advantage over other processes of fusion welding in its flexibility. Because the source of heat and the metal to be added, or the welding rod, are separate, a technique of welding may be employed that distributes the heat and rod in the most desirable manner for controlling the molten puddle and preparing the parts to be joined for fusion. The pressure of the flame, furthermore, also aids considerably in controlling the molten puddle. This flexibility is particularly desirable in position, such as overhead, welding where the molten metal must be prevented from dropping away from the desired position.

Another advantage of the oxyacetylene flame lies in the protection of the molten metal from atmospheric attack by the outer envelope of the flame. The surrounding oxygen at this point, as has been previously explained, is consumed in the final combustion stage of the flame.

There are two general methods of oxyacetylene welding, known as "forehand welding" and "backhand welding." In forehand welding the rod precedes the tip in the direction in which the weld is being made, and the tip is also generally pointed in this direction. In backhand welding the tip precedes the rod in the direction of travel and is pointed back at the molten puddle and completed weld. Backhand welding is generally employed for pipe and plate welding because of the combined economy and weld quality obtained by its application.

Multiple-flame welding is being used commercially to a much increased degree. It has been recognized that in the welding operation the source of heat is called upon to perform three functions, namely, preheating the base material, preheating the welding rod and maintaining a welding puddle. In the welding of steel plate and pipe, it has been found that the speed of welding can be considerably increased by obtaining the total amount of heat from individual flames which accomplish separately the functions of preheating the base metal, preheating the rod, and maintaining the welding puddle, in place of the old practice of using a single flame to accomplish all three functions (see Fig. 108).

Downhand welding, or welding in such a manner that the weld metal flows into the joint groove by gravity, is still predominantly used where the work can be turned, so as to provide the most convenient and economical position for welding. Vertical welding is being used to a considerable extent abroad, particularly for the welding of light steel sections. Since the area of molten metal for any given thickness is reduced to a minimum when the plates are held in the vertical position, the gas consumption in vertical welding is considerably reduced over that required for downhand welding. Speed of welding is also considerably reduced, and this factor has affected the commercial use of the vertical-welding method in this country. Vertical welding can be accomplished simultaneously from both sides as well as from one side, and plates may be welded satisfactorily without vee preparation up to an appreciable thickness.

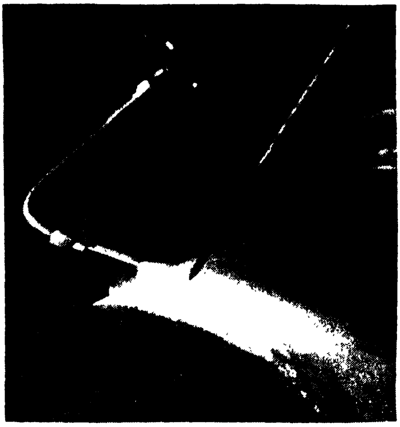


FIG. 108.—Welding with multiflame torch tip. (*Courtesy of The Linde Air Products Company.*)

Equipment.—The gas-welding equipment usually consists of a torch with separable tips, mixing heads, hoses, pressure regulators, cylinders containing oxygen and acetylene under pressure, welding rods, flux, and such accessories as goggles, friction lighter, and gloves (see Fig. 109). Mounted on a hand truck, such an outfit is readily portable and can be taken to wherever the work is located.

For large-scale welding operations, as in the fabrication of welded products, a more elaborate setup may be found useful. The oxygen may be piped throughout the shop or plant from a central point, where a number of oxygen cylinders are connected together by means of an oxygen manifold. Similarly, the acetylene may be piped from an acetylene manifold or an acetylene generator.

The *oxyacetylene welding torch* is a tool for mixing oxygen and acetylene in the desired volumes and burning the mixture at the end of a tip. Though it is true that torches vary rather widely in design, still all types have certain fundamental characteristics in common. Welding torches have a handle with two inlet connections for gases at one end. Each inlet has a valve that controls the volume of oxygen or of acetylene passing through, and thus the desired proportions of oxygen and acetylene are allowed to flow through the blowpipe, where they are thoroughly mixed before issuing from the blowpipe at the tip, or nozzle. The flame is produced by igniting the mixture at the blowpipe tip.

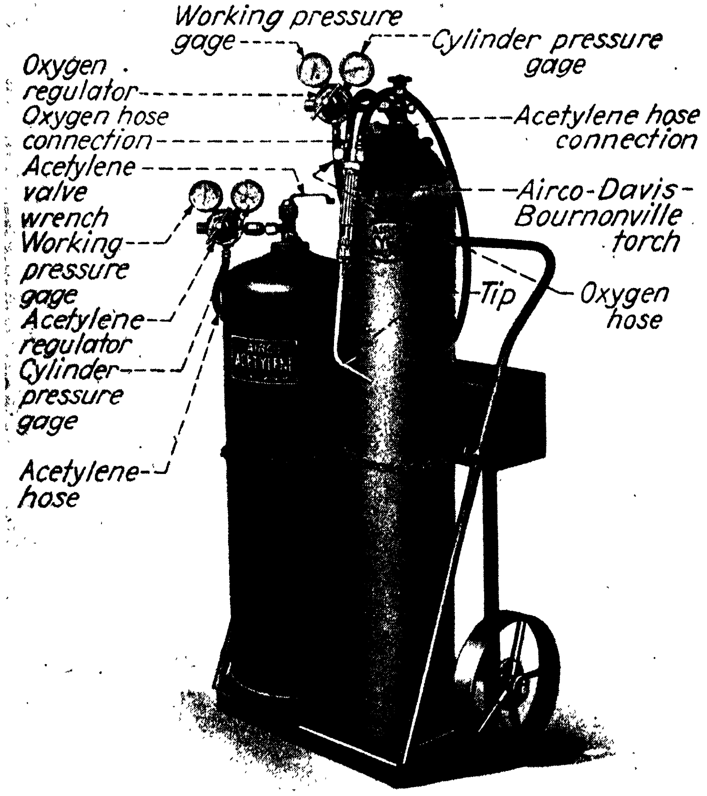


FIG. 109.—Oxyacetylene welding equipment. (*Courtesy of The Air Reduction Sales Company.*)

Some *tip* sizes usable for plates of different thickness are shown in Table I; but it must be kept in mind that there is no standardization in tip sizes, and thus the table gives approximations only. The pressures are correct for the tip-orifice size indicated.

The *hose* for welding torches should be strong, durable, nonporous, and as light as is consistent with strength and durability. Two lengths of hose, one for oxygen and one for acetylene, are required to connect the regulator and the torch. They should not be interchanged. Green is the standard color for oxygen hose and red for acetylene.

Special *hose fittings* or connections are provided for attachments to the torch and pressure regulators. These connections should not be interchangeable.

TABLE I.—TIP SIZES, PRESSURES, AND GAS CONSUMPTION

Tip size	Diameter of tip-orifice, in.	Plate thickness	Rod diameter, in.	Average length of flame, in.	Approximate pressure of regulators		Approximate consumption of gas, cu. ft. per hr.	
					Acetylene	Oxygen	Acetylene	Oxygen
1	0.037	22–16 gauge	1/16	3/16	1	1	4.0	4.0
2	0.042	1/16–1/8 in.	1/16–1/8	1/4	2	2	5.0	5.0
3	0.055	1/8–3/16 in.	1/8	5/16	3	3	8.0	8.0
4	0.063	3/16–5/16 in.	3/16	3/8	4	4	12.0	12.0
5	0.076	5/16–7/16 in.	3/16	7/16	5	5	19.0	19.0
6	0.086	7/16–5/8 in.	1/4	1/2	6	6	23.0	23.0
7	0.098	1/2–3/4 in.	1/4	1/2	7	7	35.0	35.0
8	0.1065	5/8–1 in.	1/4	9/16	8	8	48.0	48.0
9	0.116	1 in. or over	1/4	5/8	9	9	57.0	57.0
10	0.140	Heavy duty	1/4	3/4	10	10	95.0	95.0
11	0.147	Heavy duty	1/4	7/8	10	10	100.0	100.0
12	0.149	Heavy duty	1/4	7/8	10	10	110.0	110.0

The function of the *pressure regulators* is to reduce the pressure of the gas flowing from the cylinder to the required working pressure in the torch and to regulate the flow volume. A pressure regulator has a union nipple for attaching to the cylinder and an outlet connection for the hose leading to the blowpipe. There are two gauges on the body of the regulator, one showing pressure in the cylinder, the other the working pressure being supplied to the blowpipe. The working pressure is adjusted by means of a hand screw. When this pressure-adjusting screw [illegible] turned to the left (counterclockwise) until it runs free, the valve mechanism inside the regulator is closed. No gas can then pass to the blowpipe. As the handle is turned to the right (clockwise), the screw presses against the regulating mechanism, the valve opens, and gas passes to the blowpipe at the pressure shown on the working pressure gauge. Changes in this pressure are made at will simply by turning the handle until the desired pressure is registered.

Oxygen is usually shipped compressed in steel *cylinders*. The latter are usually made of drawn steel without seams and are carefully heat-treated so as to develop great strength and toughness. Each cylinder is equipped with a high-pressure valve and valve-protector cap.

Oxygen cylinders are usually charged with oxygen at a pressure of 2,000 lb. per sq. in. at 70°F. Frangible disks and fusible plugs are usually positioned in the cylinder valves for the purpose of relieving the cylinder of its content in case it is subjected to overheating or excessive pressure from any cause.

The high charging pressure makes it possible to put 220 cu. ft. of oxygen into a cylinder about 56 in. tall and of 9 in. diameter and 110 cu. ft. of oxygen into a cylinder about 48 in. high and of 7 in. diameter.

Acetylene is usually stored in cylinders containing approximately 100 to 300 cu. ft. of free acetylene under an initial pressure of about 250 lb. per sq. in. at 70°F.

Acetylene cylinders are usually closely packed with absorbent filler. This packing is saturated with acetone, and the compressed acetylene is dissolved in the acetone. There is very little chance of voids being present, and thus a collection of an appreciable volume of undissolved acetylene under high pressure is prevented.

Acetylene cylinders are fitted with high-pressure valve, valve-protector cap, and fusible plugs to relieve overpressure.

Where large amounts of acetylene are required, it may be advisable and economical to generate the acetylene on the spot, using for this purpose a suitable acetylene *generator* (see Fig. 110).

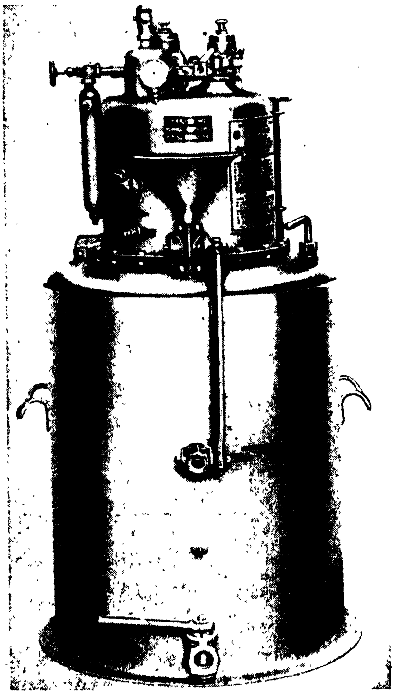


Fig. 110.—Acetylene generator. (*Courtesy of The Linde Air Products Company.*)

Goggles, fitted with colored lenses that exclude harmful heat and the ultraviolet and infrared rays, should be worn by the operator when using welding torches.

A *spark lighter* provides a convenient and instant means for lighting torch.

Setting Up Apparatus and Adjustment of Torch.—The setting up of the apparatus, the turning on of the gases, the adjustment of the pressures, the lighting of the torches and shutting down should be carefully carried out. The actual procedure is described and illustrated in Figs. 111 to 120.

A number of warnings might be given for the safe conduct of the procedure:

1. Oil or grease should not be used on cylinder valves, regulators, or torches.

2. Leaking or damaged apparatus should not be used. If a cylinder valve leaks, the cylinder should be taken out of the shop and the shipper should be notified at once. If torches or regulators leak, they should be repaired and tested by the manufacturer. If hose leaks, it should be immediately exchanged for sound hose.

3. The torch should not be lighted with both torch valves open.

4. The hose should be kept from kinking and free of obstructions, and excessive hose lengths should not be used.

5. The torch flame and sparks should be kept away from the hose, regulators, and cylinders. The hose should be kept away from heated metal.

6. Cylinder valves should be closed when not in actual use.

7. The regulator-adjusting screw should not be tightened to the limit in order to bleed the cylinders.

8. Regulator-adjusting screws should be released when not in use.

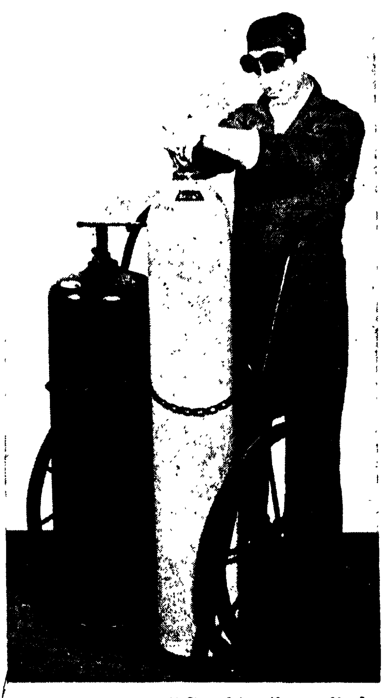


FIG. 111.—"Cracking" cylinder valves. (Each valve is opened for an instant to blow dirt out of nozzles. The connection seat is then wiped off with a clean cloth.) (*Courtesy of Air Reduction Sales Company.*)

Application of the Oxyacetylene Process to the Welding of Different Metals. *Cast Iron.*—The repairing of broken gray-iron castings by the oxyacetylene process is readily accomplished by fusion, cast-iron welding rods being used. Also, it may be accomplished without fusion of the base metal, by bronze welding, a bronze rod suitable for the purpose being employed.

Castings to be fusion-welded with cast-iron filler metal should, as a rule, be preheated to a low red heat after the edges have been prepared by beveling. The joint is made by bringing the blowpipe into play along the groove and adding to the puddle of molten cast iron additional metal from a cast-iron welding rod having a high percentage of silicon. The puddle is covered by a suitable flux which reduces the oxides formed in fusion of the base metal and welding rods.

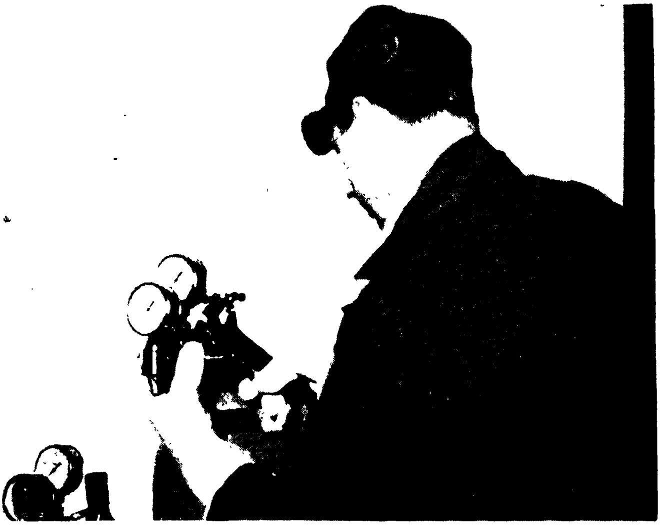


FIG. 112.—Attaching pressure regulators. (The pressure regulators are connected to the corresponding cylinders. The nuts are screwed tightly with a close-fitting wrench.) (*Courtesy of Air Reduction Sales Company.*)

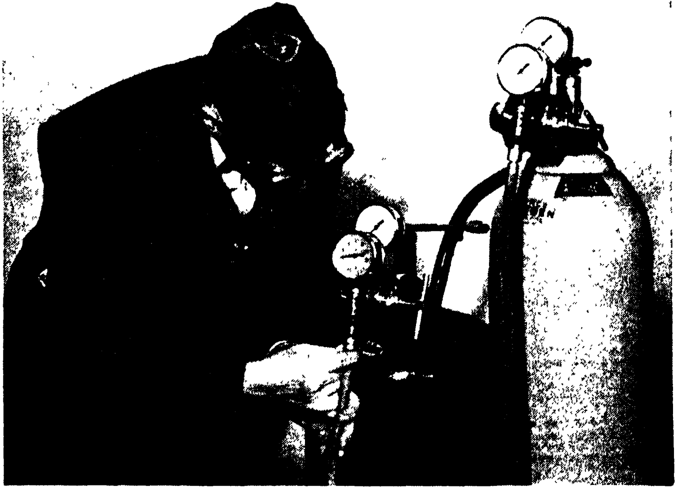


FIG. 113.—Connecting hoses to pressure regulators. (The red-colored acetylene hose is connected to the acetylene pressure regulator, and the green-colored oxygen hose to the oxygen pressure regulator. The nuts are screwed tightly.) (*Courtesy of Air Reduction Sales Company.*)

When the weld is completed, the whole preheated casting should be covered with asbestos paper and allowed to cool slowly to room temperature. After this procedure, the weld will be strong, yet soft and machinable. Hard welds will result from little or no preheating or from the use of unsuitable foundry cast iron for filler.

When broken castings are bronze-welded, comparatively little preheating is necessary. The broken edges are beveled to form a narrow vee, and the bronze is deposited without actually fusing the cast iron. If the base metal is raised to a temperature of 1600 to 1650°F., the bronze will "tin" the cast-iron surface and make a bond as strong as, or stronger than, the cast iron.

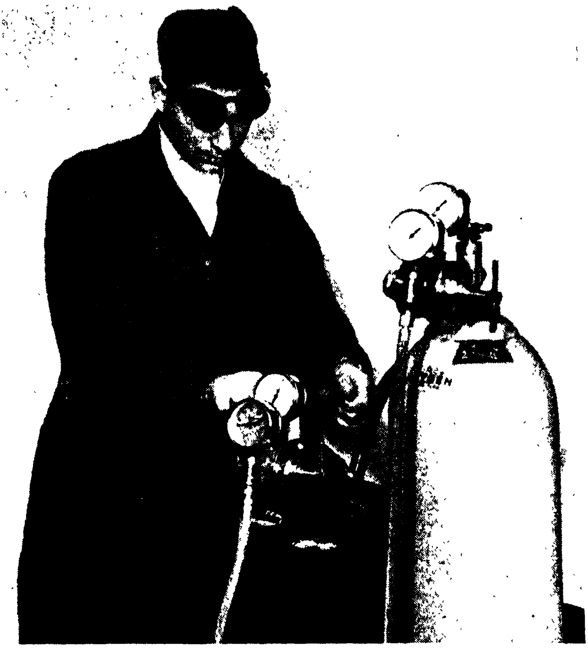


FIG. 114.—Opening cylinder valves. (The pressure regulator screws are released, and the cylinder valves are opened slowly. The cylinder valves should never be opened unless the pressure regulator screws have been released.) (*Courtesy of Air Reduction Sales Company.*)

Although the cost of bronze welding rods is considerably higher than that of cast-iron rods, the saving of preheating expense, the reduced time for annealing, the rapidity of welding, and also the dependability of bronze welds make this type of welding repair generally preferable.

Alloy Cast Iron.—The welding of the alloy cast irons should be undertaken with filler materials of very much the same composition as the base metal, and preheat should be utilized.

The repair of the alloy cast irons can be accomplished with bronze-welding materials so as to have quite high strength. An adequate

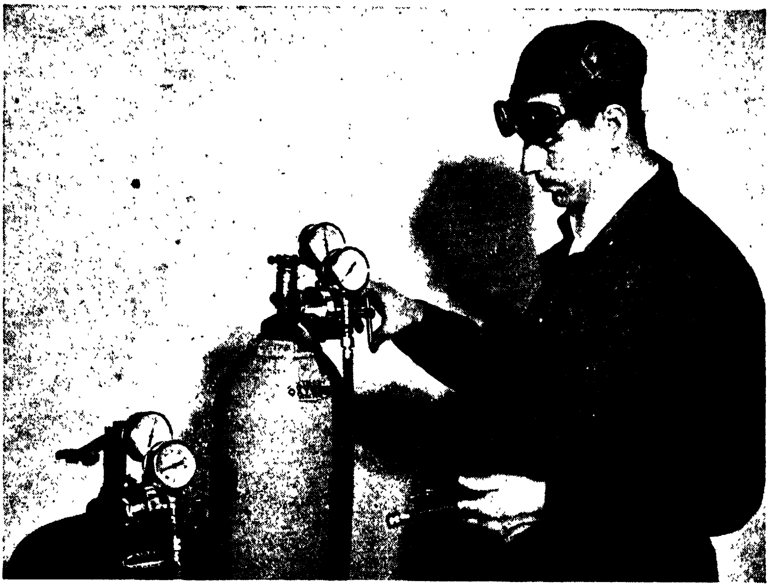


Fig. 115.—Blowing out hoses. (Pressure regulators are opened with the regulator screws, and each hose is blown out. Pressure regulator screws are then released.) (*Courtesy of Air Reduction Sales Company.*)

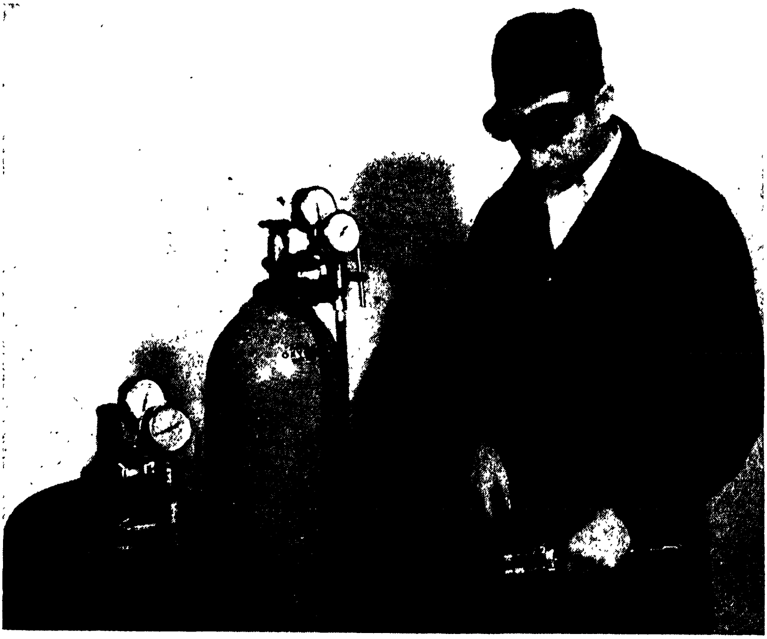


Fig. 116.—Connecting hoses to torch. (Acetylene hose is connected to the torch needle valve marked "AC," and oxygen hose is connected to torch needle valve marked "OX.") (*Courtesy of Air Reduction Sales Company.*)

reinforcement should be provided, however, in order to increase the strength of the broken section.

Malleable Iron.—The important application of oxyacetylene welding in the malleable-iron industry is the salvage of defective white-iron castings before malleableizing. They are readily welded, or built up, with the torch to remedy defects. White-cast-iron welding rods of approximately the same analysis as the base metal are used in this welding operation. Bevel preparations for welding thin sections should be made by grinding. Bevels in heavy sections can be cut with the cutting torch. The salvaged castings are then put through the malleableizing process with uniformly satisfactory results, in respect to both appearance and strength.

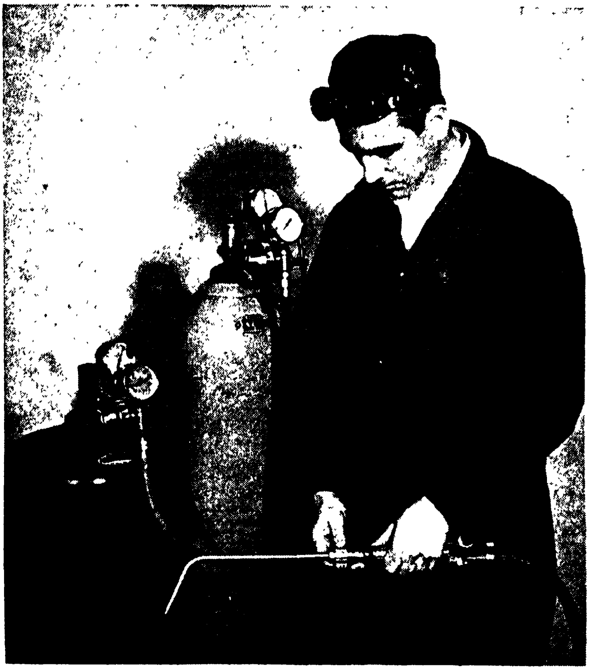


FIG. 117.—Adjusting welding tip. (Tip nut is slipped over mixing head; tip is screwed tightly into mixing head; tip nut is screwed into torch handle and tightened by hand so that tip is at proper angle.) (*Courtesy of Air Reduction Sales Company.*)

Fusion welding of malleable castings, after having been put through the malleableizing process, is generally regarded as unsatisfactory, even when the castings are remalleableized afterward. For this reason, repairs to malleable castings are generally made by bronze welding. The temperature of 1600°F. required in the base metal for bronze welding is not so high as to affect seriously the physical characteristics. Strong, effective repairs thus made are quite satisfactory to the user who is not troubled by the obvious appearance of repair. Bronze welds are made with the usual bevel preparations and a suitable welding flux.

The malleable casting maker cannot, as a rule, avail himself of the bronze-welding process if ordinary bronze welding rod is used, for the typical brass color of the weld betrays the repair and causes rejections by purchasers' inspectors. The introduction of bronze welding rods of high nickel content has eliminated the color difference between the weld and the base metal to a great extent, however.

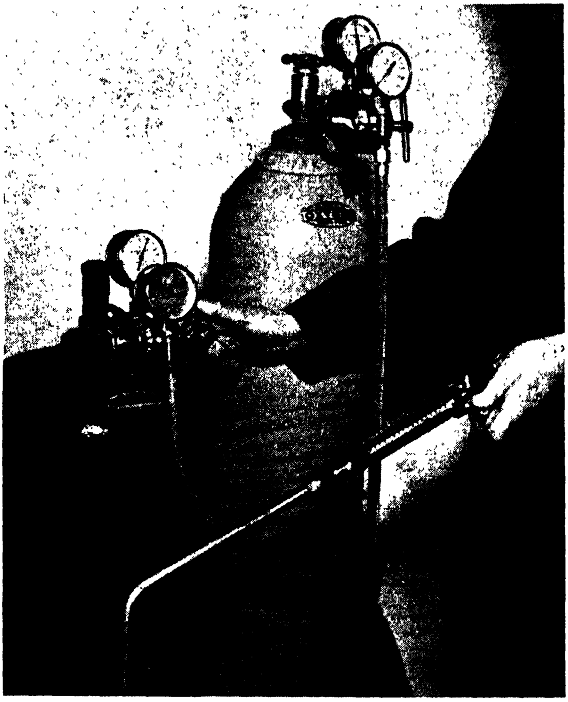


FIG. 118.—Adjusting working pressures. (Acetylene-torch needle valve is opened, and acetylene regulator is adjusted to required working pressure. The acetylene-torch needle valve is then closed. The oxygen working pressure is adjusted in same manner.) (*Courtesy of Air Reduction Sales Company.*)

Hence, the salvage of castings in the malleable-iron industry can now be affected in both stages of production: (1) in the white-iron state, preferably by use of white-iron filler rod, and (2) in the finished state, by use of a somewhat costly nickel bronze rod, making a typical bronze weld of steel-gray color, rather than the golden color of bronze.

Wrought Iron.—Although a sweated or greasy surface is usually regarded as an indication of an approach to a temperature suitable for welding with other metals, this appearance is deceptive in the case of wrought iron. The iron silicate content sweats to the surface at a comparatively low temperature and is likely to deceive the inexperienced welder who may regard it as an indication of fusion. However, heating must be continued until the base metal itself actually breaks down into a puddle. This puddle of molten metal must be maintained and the welding rod kept immersed in it to ensure fusion and penetration without oxidation. Excessive stirring of the puddle should be avoided, for this causes undue exposure and resulting oxidation.

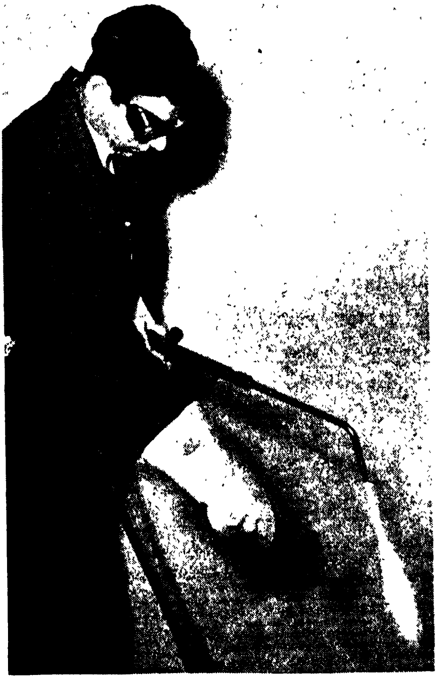


FIG. 119.—Lighting torch. (Acetylene-torch needle valve is opened, and acetylene is ignited at end of tip with spark-lighter.) (*Courtesy of Air Reduction Sales Company.*)

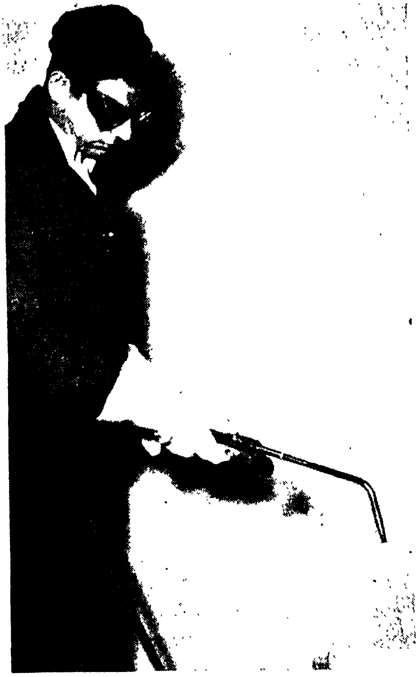


FIG. 120.—Adjusting for wanted flame. (Oxygen-torch needle valve is opened and adjusted for wanted flame.) (*Courtesy of Air Reduction Sales Company.*)

The bevel for the welding vee should have a 90-deg. included angle with shoulder. The height of the shoulder should be not more than one-sixth the thickness. All cutting oxide should be removed.

The welding rod for wrought iron either should be a low-carbon rod or should contain sufficient manganese and silicon so that a weld metal relatively high in these elements will be obtained.

The weld flame should be strictly neutral, and it should be applied until the base metal breaks down completely into a molten puddle.

The torch tip should be manipulated with a semicircular movement to distribute the heat evenly, care being taken that both sides of the vee are equally heated and fused. The welding rod should be melted by immersion in the puddle and by the indirect heat of the flame. The rod should be manipulated with the minimum of movement required for uniform fusion and penetration.

The welding rod should be of a diameter suitable for the thickness of the parts to be welded—1/16 in. in diameter for a 1/8-in. sheet to 5/16 in. in diameter for heavy sections.

Low-carbon and Medium-carbon Rolled Steel.—The metals that are most used for industrial fabrication at the present time are low-carbon and medium-carbon rolled steel. This is on account of the strength of the material, its workability under fabricating methods, and its relatively low price.

The high melting temperature of steel, about 2700°F., compels the use of acetylene with oxygen in the fusion-gas-welding process, and, owing to greater efficiency of deposition of metal, it is also necessary to use acetylene as a fuel gas in bronze-welding steel.

In welding long seams in low-carbon steel, allowance must be made for the effect of the heat along the line of the weld; for the deposited metal, in contracting during cooling, will tend to shorten the width of the weld and thus to pull the unwelded ends of the sheet toward each other. The usual spacing that is allowed in welding is about 1/4 in. for each foot of seam. With faster welding methods recently developed, this spacing can be decreased to approximately one-half this amount.

During the welding operation, the edges to be joined should be kept in the same plane if a butt weld is being made. For fillet welds, the overlapping edge should be kept close to the under edge. In butt welds, it is also highly advisable to keep the edges very slightly separated at the bottom of the joint, for this practice is conducive to good penetration. Serious pinching together of the edges will mechanically prevent fusion of the metal entirely to the bottom as would occur under normal welding conditions.

Under some conditions, jigs are used to hold the steel during the welding operation, and these almost always make proper allowances for the stresses.

The filler metal to be added during the welding of steel has changed from that originally used, which was a very low-carbon iron or steel rod, until at the present time the preference is for so-called "high-test" welding rods. The latter contain about 15 to 20 points of carbon and have certain metallic elements that ensure freedom from included oxides and also give the proper degree of fluidity in the molten metal.

Steel may be bronze-welded quite readily. In this operation, as the joint is being made, the surfaces of the steel are "tinned" through use of suitable flux and a suitable bronze welding rod. The bronze is then melted into the space between the tinned surfaces to be joined. This work is ordinarily done as a continuously progressing operation, the tinning being carried out for a distance, and then additional bronze is deposited before the section becomes cold.

Practically all welding of ductile materials, such as wrought-iron and alloy steels, is carried on in a manner similar to that for the welding of low-carbon steels.

High-carbon Steels.—High-carbon steels are generally used for tool bits, dies, springs, saws, cutlery, and other similar metal articles. Suitable welds can be made in high-carbon steel through the use of a high-carbon steel rod. In welding this metal, harder and better welds will be obtained if an excess of acetylene is used in the welding flame. The quality of the joint will be greatly improved if it is heat-treated after it has been completed.

Cast Steel.—Welding of low-carbon-steel castings, up to 0.10 per cent carbon content, offers no difficulty as a rule, if ordinary precautions are taken to avoid setting up excessive expansion and contraction stresses and the job is cooled slowly after welding.

Castings broken in service should be preheated for welding and annealed after welding whenever feasible to ensure elimination of residual casting strains and local stresses set up in welding.

Procedure on medium-carbon-steel castings, 0.10 to 0.25 per cent carbon, is essentially the same as that outlined in the foregoing paragraphs. Welding rods, however, should be of higher-tensile strength. Annealing after welding should always be done when feasible.

High-carbon-steel castings, 0.25 to 0.55 per cent carbon, should be carefully inspected in the foundry for all defects, and welding should be done before annealing with welding rods of high tensile strength, not less than 85,000 to 90,000 lb. per sq. in. when deposited.

Preparation of castings broken in service and requiring beveling with the torch should be made while the parts are warm, and then the casting should be raised to a temperature of approximately 1000°F. for welding. When the welds are finished, the temperature should be raised to 1500°F. and the casting annealed by slow cooling.

Bronze welding can satisfactorily be used on steel castings, especially for reclamation when the surface appearance of the castings is of slight importance. Otherwise, the difference in color, being readily noticeable, will detract from the appearance of the finished casting.

Tool Steels.—Tool steels, defined as carbon steels, containing 0.60 to 1.50 per cent carbon and made by the crucible process, present no great welding difficulties, especially if in the lower carbon ranges.

Wrenches, arbors, chisels, hammers, sinking dies, picks, tampers, and most other tools require uniform-temper hardness in the working faces.

Therefore, rods used for welding repairs should be selected for carbon content that will ensure weld deposits having carbon percentages at least equal to the base metal and of nearly the same physical characteristics when hardened and tempered. Welding requires correct flame adjustment, careful manipulation of flame and rod, and, usually, preheating before welding and reheating and slow annealing following the operation.

In welding tool steel, the base metal should be broken down as little as possible. If the welding is done with a strictly neutral flame and puddle, the groove should be of a width that affords access and penetration at the bottom, with little fusion of the groove side walls. Flux suitable for cast-iron welding should be used, but it must be added sparingly.

Preheating of large tools, especially those having cutter teeth widely spaced, is advisable to reduce heat-expansion stresses and to favor uniform weld deposits. When welding is completed, the whole tool should be heated to about 1500°F. and annealed by slow cooling, if it is not to be hardened and tempered. If the whole tool is to be hardened, the annealing operation is not required, and it should be immediately heated to hardening temperature, quenched, and tempered.

In welding tool-steel bits to low-carbon-steel shanks, the flame should be played on the shank more than on the bit to ensure uniform fusion, or sweating. This is necessary because the fusion temperature required for low-carbon steel is higher than for the tool steels of higher carbon content.

Stainless Steel.—Practically any of the stainless alloy steels can be satisfactorily welded by the oxyacetylene process if the proper procedure is carefully followed. However, it is highly recommended that whenever possible detailed instructions as to the proper procedure should be obtained from the manufacturer of the alloy before any welding is attempted. In general, the procedure for welding low-carbon rolled steel, using the excess-acetylene flame, should be followed, with exceptions as noted for various classes of alloy steel.

The oxidation of the alloying metals in stainless steels must be carefully guarded against. This is best done by using a suitable flux which should be made into a thin paste and painted along the edges to be welded. It is vital that the lower face of plate surfaces be coated with flux to prevent oxidation from the root, or lower part, of the weld upward into the deposited metal or along the edges of the base metal.

Low-chromium Steels.—The alloy steels containing low percentages of chromium, such as the 1 per cent chromium steel, are readily joined by oxyacetylene welding, the usual method employed for the higher chromium alloys being used. In most cases, the strength and ductility of the weld and the adjacent base metal will be greatly improved by subsequent heat-treatment.

4 to 6 per Cent Chromium Steel.—These alloys can be satisfactorily welded by the oxyacetylene process. Though all will air-harden when heated above 1550°F. unless they contain a carbide-forming element such as columbium, the lower carbon-content alloys will be affected the least and, therefore, are to be recommended for welding. The completed welds should be relieved by annealing at 1400°F. and cooled in air. As with higher chromium steels, a slightly carburizing flame should be used. A rod of the same analysis is to be preferred.

Nickel Steels.—Nickel steels of the S.A.E. (Society of Automotive Engineers) type can be readily oxyacetylene-welded with the use of a suitable nickel-steel welding rod. With a rod of proper composition, the weld metal responds to heat-treatment in practically the same manner as the nickel-alloy base metal. Heat-treatment will eliminate the possibility of heat cracks, which may develop in welding nickel steels of this type.

Manganese Steels.—Manganese steels, containing 1 to 2 per cent manganese, can be readily joined by oxyacetylene welding, the ordinary carbon-steel-welding procedure being used. A manganese-tungsten, a manganese-molybdenum, or a nickel-vanadium steel rod should be used for satisfactory results.

Copper.—Commercial copper sheets and bars are generally pitch or electrolytic copper, produced 99.9 per cent pure. The poling process employed in melting the anodes reduces the oxygen content to 0.03 to 0.07 per cent.

Copper containing small percentages of silicon, phosphorus, or other deoxidizer is commonly designated as "deoxidized" copper to distinguish it from commercial or electrolytic copper.

Use of deoxidized-copper welding rod is necessary, of course, to ensure a weld having the characteristics of the deoxidized base metal. Deoxidized-copper welding rods are also recommended for fusion welding of electrolytic-copper sheets and bars.

Copper melts at about 1981°F. and is readily welded by the oxyacetylene process when copper welding rods and suitable flux are used.

The rate of heat transfer in copper is higher than in steel of the same thickness. Therefore, it is usually necessary to use welding tips one or two sizes larger than in fusion-welding steel plates of equivalent thickness.

Copper plates thicker than 3/16 in. should be beveled at the edges to form a welding vee, of about 90-deg. included angle, when placed together for welding. The edges should be set out of parallel about 5/16 in. to each foot of vee. Welding clamps for holding the edges in line and absorbing the heat are desirable in making long welds in copper plates.

Copper, unless deoxidized, contains a small percentage of oxygen in the form of cuprous oxide, and welding tends to increase the cuprous oxide contained at the grain boundaries next to the welding vee and thus to reduce the strength in the zones parallel to the weld. Great care is required in welding to minimize this effect by keeping the welding puddle covered with the flame until the weld is fully built up, by sparing use of flux, and by rapidly finishing the weld as it is made, the necessity for reheating being always avoided. The incandescent flame cone should be held somewhat high; this, together with a neutral flame, tends to give the flame a slightly oxidizing characteristic. This procedure, with the small quantity of flux that it involves, ensures an oxide protective film on the puddle and thus reduces the formation of cuprous oxide in the weld zones.

Commercial copper can be satisfactorily welded with bronze welding rods without impairment of base-metal strength when care is taken to hold the temperature down to the fusing point of such rods—1550 to 1600°F. Bronze welding is recommended for copper welds where it is not necessary to preserve uniform appearance or a continuous copper bond.

Copper is satisfactorily brazed or soldered with silver solders and alloys having fusing temperatures of 1175 to 1450°F. Other low-fusion-temperature alloys are available for similar operations on electrical connections requiring high conductivity.

Brass and Bronze.—Bronzes are alloys containing, mainly, copper and tin. Brasses are alloys containing, mainly, copper and zinc with small amounts of other metals.

There are so many different types and compositions of brass and bronze on the market that it is almost impossible to secure a welding rod of exactly the same composition as the piece to be welded. However, special bronze welding rods are in use that will give good results over a wide field of different brass compositions. A bronze-welding flux of suitable composition is also necessary for bronze welding.

The blowpipe or torch is adjusted with a neutral flame or with a flame having a slight excess of oxygen. The operator should avoid bringing the inner cone in contact with the metal. When the metal is hot enough to permit "tinning," the welding rod is added. If white fumes of zinc oxide appear, this condition indicates that the metal is being heated to a higher temperature than is necessary. The loss of zinc thus resulting should be avoided, for it will alter the composition of the weld and the adjacent base metal.

Aluminum.—Aluminum, both in the cast and in the sheet form, presents special problems in welding on account of some of its unusual properties. Its rate of thermal conductivity is high, and its melting point is low. Owing to these factors, the base metal draws heat rapidly away from the welding flame into the colder metal. Also, through a change of color, as with other metals, there is no indication that it is approaching welding heat. On being heated, it appears in form and color exactly the same until it approaches the melting point, and then it suddenly collapses.

On account of its great weakness when hot, therefore, it is often advisable to support the metal with jigs or fixtures during the welding operation.

When aluminum is melted and exposed to the air, an *oxide* forms on the surface of the fluid metal. This thick, heavy scum forms very rapidly at low temperatures and has a melting point much higher than aluminum itself. For this reason, it does not form a fusible slag on the surface and must be removed for sound welding. To remove the excess oxide from the aluminum, two methods are employed: (1) The use of flux, the usual method in welding sheet or plate aluminum, for which special material must be made; fluxes made for welding other metals are not suitable. (2) The use of a steel scraper or paddle to skim the surface of slag off the molten puddle.

Various types of aluminum now on the market differ considerably in composition and properties, both in the rolled and cast condition.

Sheet aluminum is the commercially pure metal that contains about 99 per cent aluminum and 1 per cent or less of other metallic constituents. This is commonly known as 2S. Another grade of aluminum contains approximately 1 per cent manganese in addition to the other elements. These two types of aluminum have about the same welding characteristics. Cast aluminum contains in addition several per cent of other metals which increase the strength of the metal.

In preparing joints for welding *light* aluminum sheet, three types of joint are commonly found: (1) the butt joint, in which the ends of the pieces are placed butting against one another; (2) a lap joint, in which the two pieces overlap one another; (3) the flange joint, in which the ends of the two pieces or of one of the pieces are flanged and on which no welding rod is used, the metal in the flange being melted down to form the weld metal.

After the type of joint has been decided on, the metal should be prepared for welding by application of *flux*. A small amount of aluminum flux is mixed with water to form a thin paste, and the edges of the joints are painted with this. Too much flux should not be mixed at one time, for it will spoil if allowed to stand too long.

The *flame* should be adjusted to *neutral*. Owing to the fact that molten aluminum oxidizes very rapidly, it is particularly necessary for the welder to see that the flame does not veer at all toward excess oxygen. In welding aluminum, the blowpipe is held at an angle of about 30 deg. to the plane of the weld to avoid blowing holes through the light metal when it is hot. The inner cone of the flame should be held not in close contact with the metal but at least ⅛ in. away from it. The blowpipe may be moved quickly along the seam, for fusion takes place rapidly. As welds should not be worked over, it is better to chip out any part of the weld that may be unsatisfactory and replace it with new metal, than to weld over it. After the weld is completed, it should be washed with hot water to remove any traces of flux.

In welding *plate* aluminum, a vee is usually made in the metal to be welded; if the metal is over ⅜ in. in thickness, it is usual to make notches in the vee at right angles to the weld, spaced about ½ to 1 in. apart. These notches help in giving greater penetration of the weld metal. The blowpipe is held at the same 30-deg. angle, the inner cone about ⅛ in. away from the metal. As soon as the metal begins to melt, the blowpipe is set in motion, the side motion being used as in welding steel. The welding rod is then thrust into the outer envelope of the flame just as the metal begins to melt; before the rod melts, the end is placed in the molten aluminum and is melted into the weld under the skin of oxide that covers the molten puddle.

Considerable ease in welding technique is to be gained by the use of a *welding rod* containing a small percentage of silicon in addition to the aluminum. This element makes for greater fluidity of the weld metal and slower cooling and allows welds to be made on cast and heavy sections with only slight preheating. Use of this rod for cast-aluminum welding makes it possible to dispense with the puddling technique.

In welding *cast* aluminum the great difference lies in the use of the paddle, or puddling rod. These paddles are made up from short sections, about a 1-ft. piece of ¼-in. steel welding rod, one end of which is heated and flattened until it is about ⅜ in. wide. The flat end should be ground smooth. This paddle is used to break up the oxide and scrape it out as welding progresses. In welding aluminum castings, the pieces should be placed with the edges to be joined in contact. It is well to use carbon block to support the pieces during welding.

In welding cast aluminum, some welders find that a slight excess of acetylene is helpful. A neutral flame, however, should be used if the welder can possibly attain that technique. An oxidizing flame should never be used.

Pieces to be welded should be preheated. On small sections, the blowpipe flame can be played over the castings; but this should be done very slowly, for the quick heat will crack the metal near the flame. A preheating furnace should be used wherever possible, especially on large pieces. Very little preheating is needed if a silicon-aluminum welding rod is used.

After the weld is finished, the completed assembly should be placed in an annealing bin covered with asbestos paper and allowed to cool slowly.

Nickel.—To prevent oxidation during the welding of nickel, the flame used should have an excess of acetylene. The envelope of the flame should cover the weld during the operation to prevent oxidation from exposure to the outside air. Backhand welding, that is, welding with the flame pointing toward the completed weld, helps to prevent oxidation and also slows up contraction during cooling. The welding should be done in a room where the air is still. This prevents oxidation caused by drafts.

A high grade of welding flux should be used, and the weld should be built up sufficiently to allow for grinding. When the weld is ground flush, the surface oxide will be removed and the finished weld will have a neat, smooth appearance. A nickel welding rod should be used. In welding light sheet, the edges can be flanged and melted down to form the weld metal. Nickel castings are welded with the same procedure as Monel-metal castings. In both these metals, it is necessary that the heat be carefully controlled to prevent cracks due to strains caused in cooling.

Monel Metal.—Monel metal is composed of about 67 per cent nickel and 28 per cent copper, the balance, 5 per cent, being such additional elements as iron, manganese, silicon, and carbon.

In welding sheet Monel metal, a neutral welding flame should be used. the blowpipe or torch tip being usually larger than that used for steel of the same thickness. Monel-metal wire or strips cut from Monel-metal sheet are used as welding rods, and usually no flux is necessary. The welding flame should be brought to bear on the joint and the outer envelope of the flame allowed to spread over the weld area. This will aid in excluding air from the weld and eliminating oxidation. The white film that forms on the surface of the molten weld metal helps to protect the metal underneath from further oxidation. The welding rod should be added by thrusting it through the film of oxide, or slag, and melting it into the weld underneath this protective covering. At the same time, particles of dirt or foreign matter should be worked up to the surface of the puddle. A little bronze-welding flux will help in making welds where there is an excessive oxide coating. Flux also helps in the welding of thin Monel-metal sheet at the proper speed.

The weld metal is built up above the surface and excessive metal ground off, the sound metal being left in the weld. In welding Monel-metal sheet, the welding should proceed continuously and rapidly to the end of the seam without taking the blowpipe or torch from the work. Attempts to reweld or smooth up are usually unsatisfactory. The welds made in Monel-metal sheet are soft and ductile, and consequently any distortion or warping can be remedied by hammering or rolling.

Cast Monel metal is similar to cast iron in that rapid cooling will set up strains and cause checking. Preheating and annealing must be done with care to ensure sound welds. All parts of the castings should be supported to prevent warping. Carbon blocks may be used to support some sections. Monel-metal castings must always be preheated for welding. For this purpose the usual preheating furnace may be used or the welding torch if the casting is very small. The castings should be brought evenly and slowly to a dull red heat, 1200°F., and this temperature should be held as steadily as possible during the welding operation. The flame should be a neutral flame unless trouble is encountered from oxidation, in which case the slight excess of acetylene will be of assistance. The blowpipe or torch flame should be kept near the work so that the enveloping cover of flame over the weld will prevent the inclusion of oxides. A small coating of oxide will cover the weld while the work proceeds, and this should not be removed, unless it hinders the welder's observation or the addition of the weld metal. Care should be taken not to push any of the dirt, slag, or oxide often formed beneath the surface of the molten puddle. Excessive oxide is due to improper preheating, or to the use of too large a welding tip or head. The oxides formed in the weld metal must be floated out in all cases; otherwise, the weld will be unsound. The metal surrounding the weld and oxides should be heated and this metal floated out, or the welding rod can be used to remove it if necessary. When the weld is completed, the casting should be reheated at an even temperature and cooled slowly in an annealing bin.

Rolled Monel metal can be readily silver-soldered by use of the oxyacetylene torch.

Hard Facing.—Abrasive wear has been a source of trouble and expense to many industries. Hard facing has supplied the solution to this troublesome problem. The machine part may be made of any metal selected for the particular application on account of its physical properties. Wherever wear occurs, a hard facing is applied with the oxyacetylene flame, supplying at that point a surface of an alloy specifically suited to resist abrasive wear. The process of hard facing makes it possible to utilize for the bulk of the machine part a steel particularly suited to the purpose in respect to its physical properties and cost and to apply a special wear-resisting alloy only in the places where needed. Wear-resisting alloys are usually of low strength and are more brittle and costly than machine steels; hence, it would be inadvisable in many cases to make the entire part of wear-resisting alloys.

BRAZING

Brazing is a method of producing strong joints in metals whose melting points are higher than that of the filler metal being used. The brazing process covers filler metals with melting points not lower than 1000°F. The base metal is not actually fused, but the molten filler metal will flow onto the properly heated and fluxed surfaces of the metals to give a bond or molecular union that has excellent strength. Bronze filler rods are generally used for brazing purposes.

Cast iron, steel, nickel, copper, and their alloys are all satisfactorily brazed, and even unlike metals can be joined by this process.

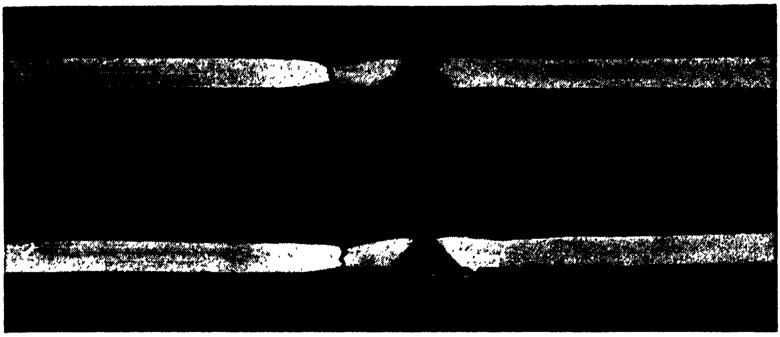


FIG. 121.—Reinforced and unreinforced tensile test coupons taken from bronze-welds on steel plate. (Fractures occurred in plates at a tensile strength of about 52,800 lb. per sq. in.) (*Courtesy of The Linde Air Products Company.*)

Brazing has its advantages and disadvantages. Since a lower temperature is needed, there is less warpage, not as much preheating is necessary, the costs are lower, there is less heat damage to the metal being welded, and the process, in most cases, is even faster than fusion welding.

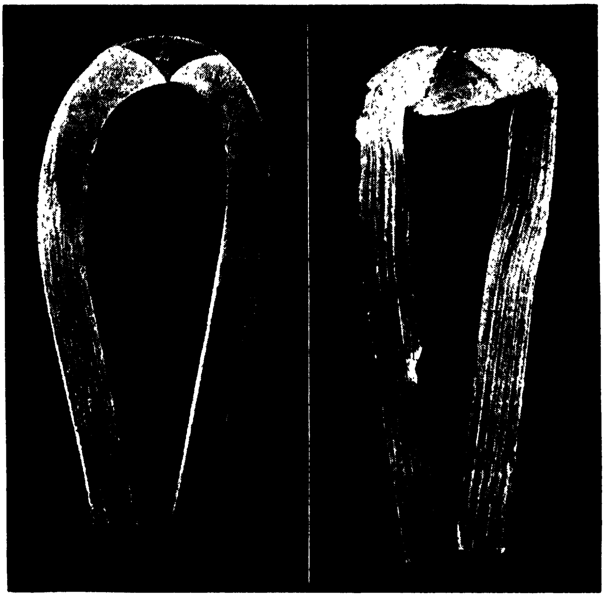


FIG. 122.—Face and root bend tests of bronze-welds on steel plate. (An elongation of 32 per cent in the weld metal was obtained in face-bend test. In root-bend test, specimen withstood considerable abuse without failure.) (*Courtesy of The Linde Air Products Company.*)

But it cannot be used if high stresses are present, or if the finished job is to be subjected to high temperatures.

There are four main brazing processes in use: gas brazing, dip brazing, electric brazing, and furnace brazing.

Gas Brazing.—This is perhaps the most important of the four brazing processes. The edges of the joint are simply heated to a dull red heat by the oxyacetylene blowpipe flame. With the base metal at the proper temperature and with the aid of the proper flux, the molten metal from the filler will unite with the base metal to form a strong bond.

The equipment required, the handling of the torch, and the actual brazing procedure are very much the same as for fusion gas welding.

Dip Brazing.—In this process, the heat is obtained from a bath of molten metal or chemical. The filler metal may or may not be obtained from the bath. The process is confined largely to the joining of small parts, especially wires and narrow strips of metal. Cleanliness and fluxing of the parts to be joined are most important. The bath must be large enough to eliminate appreciable drops in temperature, and the parts must not be immersed longer than is necessary to bring them to the bath temperature. As the parts to be joined are removed from the bath, they must be held firmly together until the filler metal has thoroughly solidified.

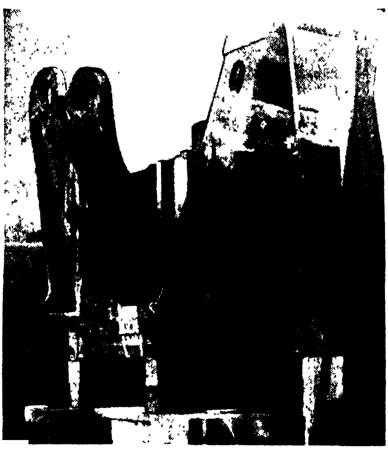


FIG. 123.—Brazing of large casting. (*Courtesy of The Linde Air Products Company.*)

Electric Brazing.—In electric brazing, the heat is obtained from an electric current through the medium of an arc, induction, or resistance. The electric-resistance method gives good results, particularly on small parts. The necessary heat is developed by the resistance of current flow in the parts at the joint, and the filler metal is applied when the joint has reached the proper heat; or the parts are pressed firmly together between carbon blocks, which serve as electrodes, after a thin sheet of filler metal has been placed in the joints. The heat generated in the blocks heats the joint. In making scarf or lap joints, electrically heated tongs are very efficient.

Furnace Brazing.—In this process, the heat is obtained from a furnace in which the atmosphere may or may not be controlled. Most standard types of heat-treating furnaces designed for muffle temperatures are suitable for brazing. As a rule, the furnace should be run at a temperature well above the melting point of the filler metal in order to heat the parts more quickly. The parts must be securely jigged with careful consideration of the effects of expansion and contraction.

Silver Soldering.—A very popular type of brazing alloy or hard solder is silver solder. It contains, as a rule, various percentages of silver, copper, and zinc. For many years, silver solders have been made in many different analyses and with many different melting points. The tendency of late, however, has been to reduce the large number of solders and produce, instead, a smaller number designed to do certain classes of work. These silver solders contain 10 to 80 per cent silver and melt at 1200 to 1800°F. Although these joining materials are usually considered high in cost, only a relatively small quantity is needed for any one joint, and consequently their cost does not seriously affect the cost of the finished product. Many operations, difficult if not impossible to perform by fusion welding, are readily and economically done by silver soldering.

Silver-solder filler metal may be obtained in the form of sheet, strip, wire, and filed, or granulated, solder.

Silver solders flow freely, are corrosion-resistant, and produce strong joints that withstand severe shocks and vibration if used at ordinary temperatures. All ferrous and nonferrous metals and alloys except those having lower melting points can be successfully silver-soldered.

Silver soldering is most commonly accomplished with the oxyacetylene flame, although, for some classes of work, any of the other processes of brazing may be satisfactorily employed.

In using the oxyacetylene flame, the joint should be thoroughly cleaned with emery cloth or steel wool and coated with a paste of good-quality silver-soldering flux. A spreading rather than a localized heat should be applied, with a larger sized tip than would be employed for fusion welding. The inner cone of the flame should be at least 1 in. away from the work. A carburizing flame will prove advantageous. The flame should not be directed against the silver solder except for momentary periods. Using an oxidizing flame and holding the torch too close to the work or on the silver solder will adversely affect the joint.

CHAPTER V

THE ELECTRIC ARC AND ITS APPLICATION TO THE WELDING PROCESS

To understand the application of the electric arc to the welding process, certain fundamental facts related to electricity should be reviewed first.

Some Principles of Electricity.—A steady current of electricity will not flow unless there is a complete conducting path or ring. Such a path over which an electric current flows is called an *electric circuit.*

An electric current flows along a conductor very much as water flows along a pipe. In order that water shall flow along a pipe, it is essential to have some driving force furnished either by a difference in water level or by a pump. In much the same way, the current will flow along a wire only if there is an electromotive force such as is furnished by a difference of potential or by an electric generator. The unit of electromotive force is called the *volt.* The electromotive force is called *voltage* or *difference of potential.* The terms refer to the same factor—the push that tends to move electricity.

The point of higher potential is called the *positive electrode,* or *anode,* and the point of lower potential is called the *negative electrode,* or *cathode.*

The rate at which water flows through a pipe may be expressed as a certain number of gallons or cubic feet per second. In the same manner, the rate of current of electricity may be expressed as a certain quantity of electricity flowing per second past a certain point. The unit of quantity of electricity is called a *coulomb.* An electric current carrying 1 coulomb per sec. is called a current of 1 *amp.* The *current,* then, may now be defined as the rate of flow of electricity, voltage as the moving force that forces the flow.

To measure the *electric power,* the voltage is multiplied by the quantity of electricity flowing per second, or the intensity of the electric current. Thus

$$\text{Electric power} = (\text{intensity of current}) \times (\text{voltage})$$

The unit of electric power is the *watt,* which may be defined as the power required to keep a current of 1 amp. flowing under a drop of 1 volt.

$$\text{Watts} = (\text{amperes}) \times (\text{volts})$$

As the watt is a very small unit of power, the *kilowatt* (kw.), which is 1,000 watts, is used.

$$\text{Kilowatts} = \frac{(\text{amperes}) \times (\text{volts})}{1{,}000}$$

Power may be defined as the rate of doing work, or the rate of expenditure of energy. The expenditure of *electrical energy* is equal to the products of the rate of doing work by the time element. Thus

$$\text{Energy (watt-hours)} = \text{current (amperes)} \times \text{voltage (volts)} \times \text{time (hours)}$$

Every current, however small, generates heat, and the relation between electrical energy and heat is given by

$$1 \text{ kw.-hr.} = 3{,}413 \text{ B.t.u.}$$

The B.t.u., or *British thermal unit,* is a unit of measure of the quantity of heat. It is defined as the $\frac{1}{180}$ part of the heat required to raise the temperature of 1 lb. of water from 32 to 212°F. This is substantially equal to the heat required to raise 1 lb. of water from 63 to 64°F.

The Electric Arc.—An electric arc consists of an incandescent stream of metallic vapors carrying an electric current. It is formed when two conductors of an electrical circuit are brought together and then separated while there is sufficient voltage available to maintain the flow of current through the intervening gaseous medium.

Electric-arc Phenomena.—Electric-arc welding may be termed as a low-voltage application for electric power. To illustrate, an arc drawn between a metal plate and a carbon electrode will operate at a potential of approximately 35 to 50 volts, and an arc drawn between a plate and a metallic electrode will operate at a potential of approximately 15 to 45 volts. Since nearly all commercial electric circuits operate at a higher potential than these, it is necessary to use electrical apparatus that will provide the proper potential.

The peculiar resistance of the arc stream must be noted. All ordinary metals, such as iron and copper, have a constant resistance at a given temperature; that is, if the current passing through them is increased, the voltage must also be increased. With the arc stream, the opposite is true; that is, a lower voltage is required to force a large current through a given arc length than is required for a lesser current.

Energy Present in the Arc.—The energy present in the arc, expressed in watts or kilowatts, may be computed by multiplying the voltage across the arc by the current flowing in the circuit. If the time element is introduced, the amount of power used can also be calculated. For instance, if a 30-volt 250-amp. arc is used for 2 hr., then the power consumed will be

$$30 \times 250 \times 2 = 15,000 \text{ watt-hr., or } 15 \text{ kw.-hr.}$$

As in the case of a circuit, the relationship between electrical energy in the arc and heat is given by the fact that 1 kw-hr. = 3,413 B.t.u. It can, therefore, be stated that the electric arc transforms electrical energy into heat.

The Use of the Electric Arc for Welding.—The heat liberated at the arc terminals and in the arc stream is used to melt the metals to be welded at the point of contact, so that they will flow together and form a solid integral mass. Thus, different parts may be joined, or material may be added to the surface of a metal.

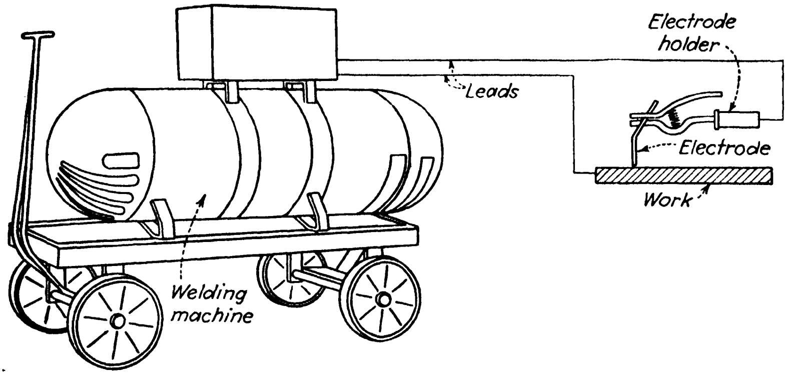


FIG. 124.—Welding circuit.

The temperature of the arc is in the vicinity of 6500°F.; and when this tremendous heat is concentrated at point of welding, it melts a small pool of metal in the work. If any additional metal is required for the welding, it is obtained from a wire or rod, which is melted by the heat of the arc and deposited into this small pool in molten state. The molten metal in the pool is agitated by the action of the arc, and thus the base, or parent, metal and the added metal are thoroughly mixed and refined so that, after cooling, a sound union is formed.

The Welding Circuit.—The welding circuit consists of a welding machine, two leads, an electrode holder, an electrode, and the work itself. They are set up in the manner shown in Fig. 124.

The Carbon-arc Process.—In the carbon-arc process, the arc is formed between the work and a carbon rod (see Fig. 125). The heat of the arc melts a pool in the surface of the work to be welded; and additional metal, when required, is supplied by a separate metal filler rod which is melted in the arc. The carbon electrode is consumed, very slowly, owing to oxidation and vaporization only. Carbon-arc-welding practice is similar to welding with the oxyacetylene flame.

The Metallic-arc Process.—In the metallic-arc process, the arc occurs between the work to be welded and a metallic wire which, like the parent metal, is melted by the intense heat of the arc (see Fig. 126). The melting wire, or electrode, thus furnishes the "filler metal" and is fed at a uniform rate toward the base metal.

Shielded and Unshielded Arc-welding Processes.—Molten steel has an affinity for oxygen and nitrogen. When exposed to the air, molten steel enters into chemical combination with the oxygen and nitrogen of the air to form oxides and nitrides in the steel. These impurities weaken and embrittle the steel and lessen its resistance to corrosion.

An ideal weld is one whose properties are equal or superior to those of the parts joined. With the arc-welding process, such a weld can be obtained by effectively protecting the molten filler metal in the arc stream and the weld metal from the oxidizing and nitrogenizing effects of the air during the entire range of liquefaction and solidification.

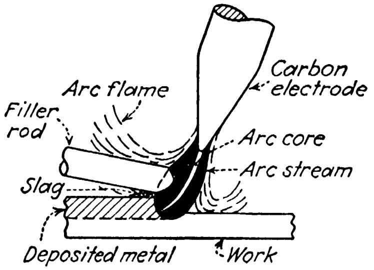


FIG. 125.—Carbon-arc welding.

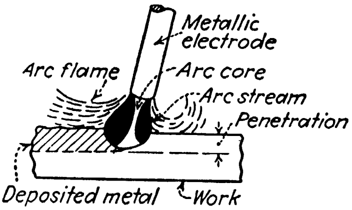


FIG. 126.—Metallic-arc welding.

An arc may be shielded by completely enveloping it with an inert gas that will not enter into chemical combination with the molten metal and that at the same time will prevent the molten metal from coming in contact with the atmosphere.

Arc-welding processes, in which the molten filler, weld, and base metals are effectively protected, are classified as *shielded processes* to distinguish them from *unshielded processes* in which no protection or only partial protection is given.

Coated- or *covered-electrode welding* includes all processes in which shielding is accomplished by combustion, vaporization, or melting of the several ingredients of the covering applied to the wire core of the electrode.

Taper-shielded welding includes all processes in which a ribbon or cord is independently and automatically fed into the arc zone and functions like the coverings on coated electrodes.

Gas-shielded welding includes those processes wherein the arc zone is surrounded by an inert gas supplied from an independent source.

Flux-shielded welding includes all processes in which a flux in the form of a paste or powder is placed in or at the point ahead of the arc and is wholly or partly vaporized, or melted, as the welding proceeds.

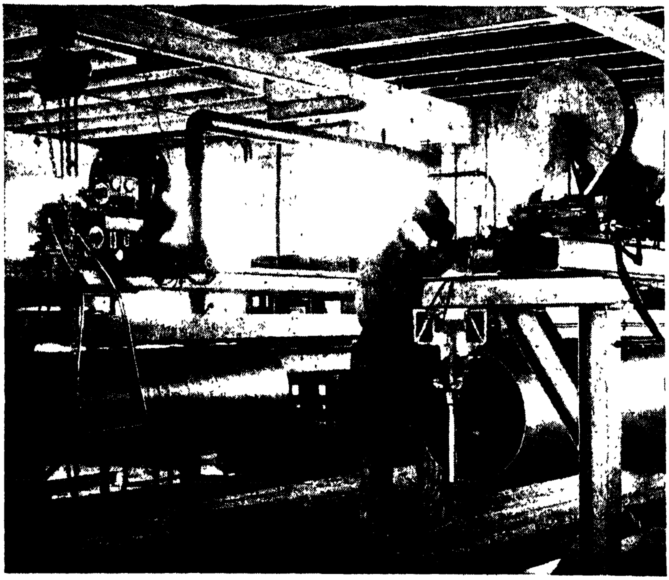


Fig. 127.—Automatic welding heads and travel carriages used in fabrication of pipes. (*Courtesy of General Electric Company.*)

Bare-electrode welding, an unshielded process, includes the use of lightly-coated electrodes as well as truly bare electrodes.

Manual and Automatic Operation.—Arc welding may be done by *hand* operation or *automatically* by machine. In the manual method, which is the most common, the electrode is gripped in a holder which the operator grasps in his hand. In the automatic method, used where the nature of the work permits, the electrode is manipulated by machine.

CHAPTER VI

ARC-WELDING EQUIPMENT

In general, arc-welding equipment consists of a source of welding current, electrodes, electrode holders, cables, protective equipment, and a number of miscellaneous tools that are used by the welding operator in the performance of his daily work. Since any of these items may have a direct or indirect effect upon the ultimate quality of a weld, it is important to have an intelligent understanding, not only of their functions, but of their desirable properties as well.

SOURCE OF ARC-WELDING CURRENT

The Welding Arc and Its Electrical Requirements.—Ordinary electric loads, such as heaters and lamps, are fairly steady in their two demands for current and voltage, but the welding arc is extremely unsteady in both. For instance, the molten globules of weld metal crossing the arc may cause electric short circuits as often as twenty times or more per second. An electric short circuit is also caused every time the operator touches the electrode to the work in order to strike an arc. Whenever these frequent instants of short circuit take place, the electric resistance of the welding circuit falls so low as to cause an excessive surge of current to flow in each instance, unless the generator is designed to prevent this from actually happening. Even with the low resistance prevailing on short circuit, excessive heat is caused by the excessive current surges. As a result, there is excessive splatter and sticking of the electrode. A good arc-welding generator is designed adequately to limit instantaneous surges of current and thus to prevent excessive splatter during welding as well as the troublesome sticking of the electrode to the work in striking the arc.

Upon short-circuiting, the voltage falls almost to zero; but the instant that each short circuit is cleared, a considerable amount of voltage is required to keep the arc going and to prevent its extinguishment. Likewise, a considerable amount of additional voltage is also instantaneously needed whenever the length of the arc is quickly changed. Therefore, the welding generator must provide adequate recovery of voltage instantaneously.

In carbon-arc welding, where there is no actual transfer of material across the arc, the inherent resistance characteristic is the only cause for instability.

Successful welding, then, requires a supply of electric current sufficient in amount for the size of electrode used, of suitable voltage for striking and maintaining the arc, and of suitable characteristics to provide stability for the arc. The voltage across the arc will, in general, range from 15 to 26 volts with the usual bare or lightly coated electrodes, from 20 to 40 volts with the usual heavy-coated electrodes, and up to 45 volts with

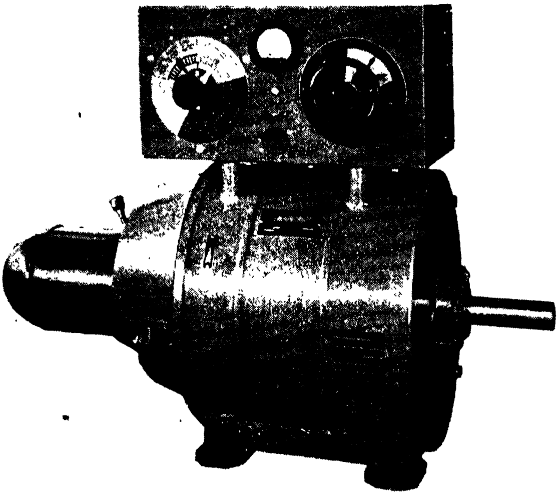


FIG. 128.—Generator for belt drive or direct connection. (*Courtesy of The Lincoln Electric Company.*)

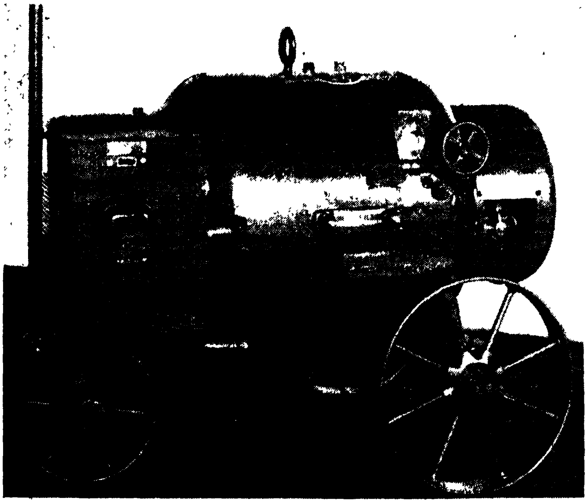


FIG. 129.—Generator driven by electric motor. (*Courtesy of Westinghouse Electric and Manufacturing Company.*)

some special electrodes. The current for manual operation of the metallic arc usually ranges from 30 to 300 amp.; for automatic operation, from 75 to 600 amp. In carbon-arc welding, the voltages range from 35 to 50 volts, and the current ordinarily from 50 to 1,000 amp.

Sources of Supply of Current.—Welding current is usually obtained from one of four sources of supply: (1) a d.c. generator with variable-voltage characteristics; (2) a d.c. generator with constant-voltage characteristics; (3) an existing d.c. power line, used in conjunction with resistors to reduce the voltage and current; (4) a special a.c. generator or transformer.

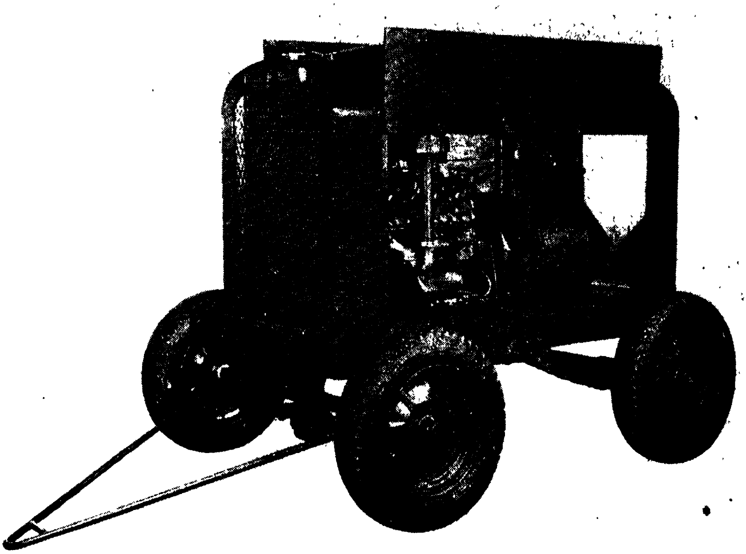


FIG. 130.—Generator driven by gasoline engine. (*Courtesy of General Electric Company.*)

The *d.c. generator with variable-voltage characteristics* is arranged so that the voltage automatically adjusts itself to the varying voltages that may be demanded by the arc. It is suitable for use in furnishing arc-welding current to one operator only, and for this reason it is commonly known as a "single-operator" arc welder. It is usually equipped with some kind of control by means of which the output can be adjusted to suit a variety of work. An electric motor or an engine of some type is generally used to drive such generators, and the weight and size of the entire unit are such that portability can ordinarily be obtained quite readily, the moving of the machine to the work without too much trouble being thus possible. This type of machine is the most widely used today and is the most economical type.

In the setup of a *d.c. generator with constant-voltage characteristics*, a resistance is introduced in series with the arc to reduce the voltage to the proper value for welding. Of course, this involves a waste because of the power lost in the resistance. This setup is used especially with large motor-generator welders, where the generator is arranged to give 60 to 100 volts direct current.

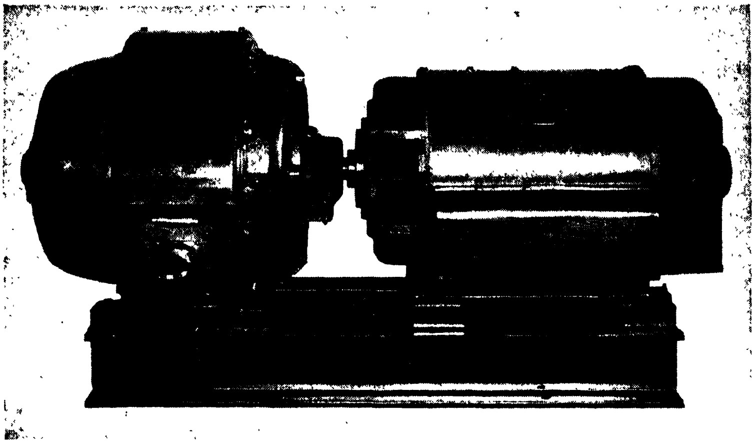


FIG. 131.—Typical multiple-operator d.c. arc-welding set. (*Courtesy of General Electric Company.*)

The "constant-voltage welder" is suitable for furnishing current simultaneously to more than one welding operator; for that reason, it is sometimes known as the "multiple-operator" type of arc welder. Of course, all the operators must be working in the same locality with electrodes of the same polarity. This use results in a considerable reduction in the original investment as well as in a saving in subsequent maintenance.

The capacity of the multiple-operator welder depends largely upon the operating factor, that is, the average percentage of time each operator is actually welding. It is not uncommon to supply as many as 20 operators using 150 to 200 amp. each from a single 1,500-amp. multiple-operator set.

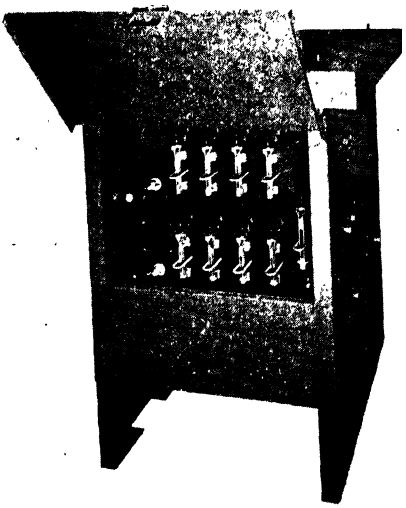


FIG. 132.—Typical resistor-reactor unit. (*Courtesy of General Electric Company.*)

In addition to the motor-generator set itself, the multiple-operator arc-welding equipment includes a resistor-reactor station for each operator, as well as a motor starter and general control panel. The drive for the generator may be an induction motor, a d.c. motor, a synchronous motor, a gas engine, or a Diesel engine. Owing to the size and weight of the set, such a machine is usually mounted in one location and is not portable (see Figs. 131 and 132).

Direct-current power lines are often available from which it may be practicable to obtain power for arc welding. This is especially true in respect to mines and street railways. To reduce the voltage and adjust the current, a resistor, with means for current adjustment, can be placed across the power line in series with the arc. Although the initial cost of equipment is not great, welding by this means is not satisfactory; for the open-circuit voltage is ordinarily too high, and the voltage characteristics are not suited to the best arc welding. However, it is used with some success for building up battered rail ends and for other types of maintenance work.

Transformers having variable-voltage characteristics usually supply alternating current for arc welding, although motor-generator sets have been used. Alternating-current arc welders are usually of the single-operator type, but multiple-operator units have also been built. Current adjustment with the transformer type is usually provided either by plugs or switches that give a definite number of adjustments of output or by a Vernier (and wheel) adjustment, which permits any current within the range of the equipment to be obtained (see Fig. 133).

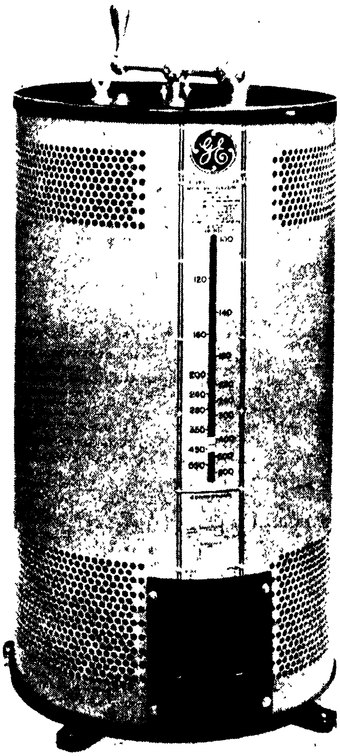


FIG. 133.—Arc-welding transformer. (*Courtesy of General Electric Company.*)

Applications of a.c. welding are becoming more and more diverse and widespread. Former limitations on its use were largely due to the lack of electrodes adequately stabilized for alternating current; today, there are many excellent a.c. rods available for mild steel welding, and they are being successfully used on all types of fabrication where welds of shielded-arc quality are required. Users report that they have changed to alternating current with no sacrifice in physical test values and are working at increased heats and speeds, often with improvement in the soundness of deposited metal over that previously obtained. This is assumed to be due to agitation of the molten pool by the pulsations of the a.c. arc, which results in refinement of the deposited metal by working out slag particles.

Troubles due to magnetic blow are largely eliminated by the use of alternating current; where arc blow is noted, a.c. welding is particularly valuable. Even where arc blow is not particularly noticeable with direct current, the improvement in the soundness and the appearance of welds in corners reported by many users may be due to the better penetration and concentration of the arc when magnetic blow is avoided by the use of alternating current.

In addition to the advantages of speed and soundness, particularly on heavy work, a.c. welding has the obvious advantage of low power cost and low maintenance expense resulting from the absence of moving parts. Power costs average only 5 to 10 per cent of the total cost of welding; but where heavy currents are being used and duty factors are low, reductions of as much as 50 per cent in the power bill are frequent.

Welding machines are tested principally for the pounds of weld metal deposited per hour, the pounds of weld metal deposited per pound of electrode used, and the pounds of weld metal deposited per kilowatt-hour of power consumed by welding machine.

Requirements for Uniform Welding.—Uniform and easy welding is best obtained with a generator that provides current adjustment to secure whatever heat is required and that does not permit this heat to change appreciably with normal variations in arc length during welding operation.

If the effective arc heat is to remain constant, more actual watts must be delivered to a long arc than to a short arc, for the heat losses from a long arc are greater than from a short arc. The generator should then be capable of automatically increasing or decreasing the average watts input to the arc to compensate for variable arc losses and keep the effective arc heat and penetration practically constant in spite of changes in arc lengths.

Some Leading Makes of Arc Welders.—There are many makes of arc welders in use in industry today. Five of the most widely used makes are those manufactured by the General Electric Company, The Hobart Brothers Company, The Lincoln Electric Company, The Westinghouse Electric and Manufacturing Company, and The Wilson Welder and Metal Company (see Figs. 128 to 133). As an illustrative example of the principle upon which these welders may operate, a detailed discussion of two types of General Electric welder follows.

General Electric Single-operator D.C. Welder (Type WD-30B). *Principle of Operation.*—This machine has two magnetic poles, each of which has two sections, one for the "main"-field winding and the other for the "cross"-field winding (see Fig. 134).

The main-field pole pieces are highly saturated magnetically, and consequently their flux is practically constant, regardless of armature reaction (the magnetic effect of the armature current). Thus, the main magnetic field produces in the armature a constant voltage of about 45 volts. This steady voltage is always available and is used as an unchanging source of constant voltage for the shunt-field winding.

The cross-field pole pieces carry the series windings of the machine, and are not saturated. Their magnetic strength is therefore largely affected by the armature-current magnetic effect, which is in such a direction as to oppose their flux.

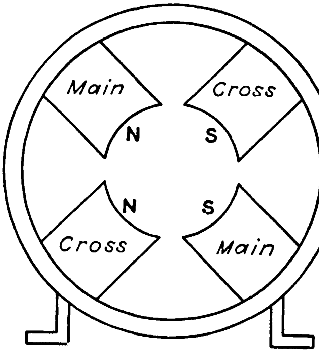


FIG. 134.—Arrangement of poles. (*Courtesy of General Electric Company.*)

The voltage at the terminals of the machine is the algebraic sum of the armature voltages produced by the main-field flux and the cross-field flux, respectively. When no armature current is flowing (open circuit), the machine voltage is high (95 volts at full field) because both the main-field and the cross-field fluxes produce armature voltages that are in the same direction. At short circuit, the main-field flux still produces 45 volts in the armature, but the cross-field flux is now reversed in direction by the magnetic effect of the heavy armature current. The terminal voltage of the generator is then the difference between 45 volts and the voltage produced by the cross-field flux. This difference is zero at short circuit.

Under actual welding conditions, the amount and direction of the cross-field flux are determined at any instant by the armature current at that instant. Thus, the terminal voltage is determined by the amount of armature current flowing. That is, the macnine is self-regulating: the voltage decreases as the current increases.

The amount of voltage decrease produced by a given welding current can be changed by changing the number of series field turns. This is done in the type WD generator by means of the tap switch on the control panel. The five-point tap switch provides five different generator characteristics at any one shunt-field current. Closer adjustment of current can be accomplished by varying the shunt-field strength by means of the field rheostat on the control panel. This adjustment has little effect on the main-field flux because its magnetic circuit is already saturated. The effect on the cross-field flux is large, because its circuit is unsaturated. Thus, current control by shunt-field rheostat is obtained without changing the main-field flux and therefore without changing the armature-voltage component which is utilized for instantaneous voltage recovery and for excitation.

The distribution of field windings on the 200- and 300-amp. machines is indicated by the schematic diagram of Fig. 136. (This diagram shows only one pole, the other being similarly composed of two pole pieces.)

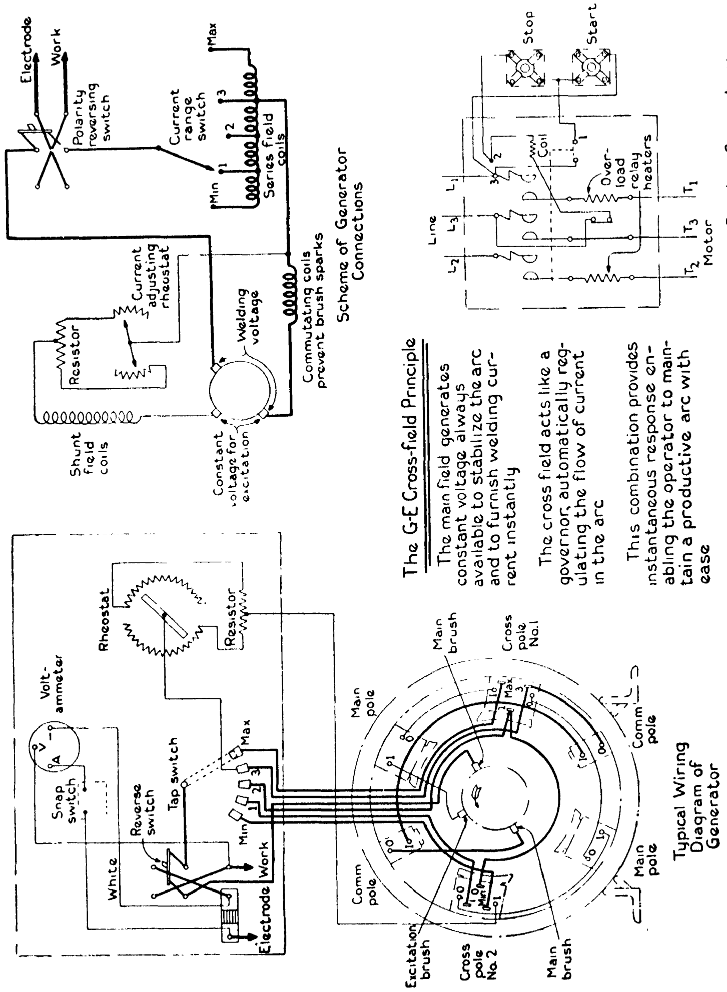

Electrode
Work
Polarity reversing switch
Current range switch
Min
1
2
3
Max
Series field coils
Current adjusting rheostat
Resistor
Welding voltage
Commutating coils prevent brush sparks
Scheme of Generator Connections
Shunt field coils
Constant voltage for excitation
The G-E Cross-field Principle
The main field generates constant voltage always available to stabilize the arc and to furnish welding current instantly
The cross field acts like a governor, automatically regulating the flow of current in the arc
This combination provides instantaneous response enabling the operator to maintain a productive arc with ease
Line
L1
L2
L3
Stop
Start
Coil
Over-load relay heaters
T1
T2
T3
Motor
Motor Starter Connections
Rheostat
Resistor
Volt-ammeter
V
A
Snap switch
Reverse switch
Tap switch
White
Work
Electrode
Min
1
2
3
Max
Main pole
Main brush
Cross pole No.1
Comm pole
Typical Wiring Diagram of Generator
Main pole
Comm pole
Excitation brush
Cross pole No.2
Main brush

FIG. 135.—Typical connection diagram for General Electric single-operator motor-generator arc welder, Type WD. (*Courtesy of General Electric Company.*)

On the 400- and 600-amp. machines, there is an additional series winding on the main pole pieces, which is cumulative to the main-pole shunt winding. Its purpose is to increase the effective reactance of the generator and to utilize the transformer action between the series and shunt windings (during transient surges of welding current) to provide additional stability in the generator.

General Electric (Type WK) Arc-welding Transformers. *Principle of Operation.*—Reactance control of the welding current is used in all type WK arc-welding transformers. In the moving coil design, the reactance of the secondary coil varies with changes in spacing between the primary and secondary coils. The welding current that will flow at a given secondary voltage is thus controlled. Since the primary coil is moved by a screw, there is an infinite number of current adjustments within the range of the welder, and adjustment can be made while welding. The moving-coil principle of current control is illustrated in Fig. 137.

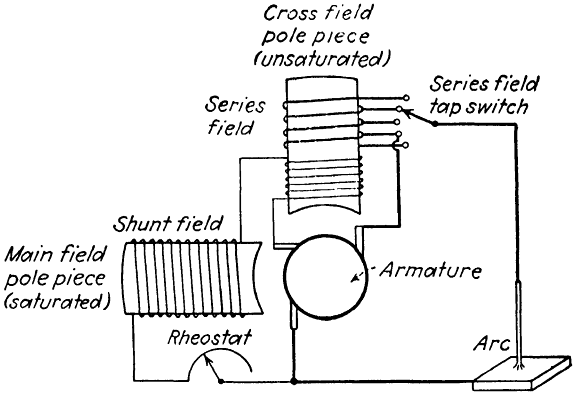
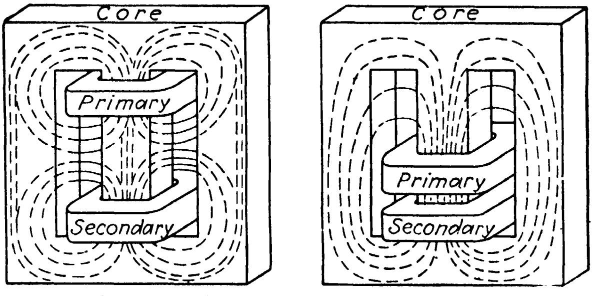

Cross field pole piece (unsaturated)
Series field
Series field tap switch
Shunt field
Main field pole piece (saturated)
Armature
Rheostat
Arc

FIG. 136.—Schematic diagram of connections WD-32 and WD-33. (*Courtesy of General Electric Company.*)



LOW CURRENT HIGH CURRENT

FIG. 137.—Control of current by leakage reactance. (*Courtesy of General Electric Company.*)

Power Factor.—Welding transformers are inherently low-power-factor devices. Where power-factor considerations are important because of power-company penalties, overloading of circuits, or selection of wiring equipment, it has been customary to recommend capacitors as an additional item to improve power factor. On the 300- and 500-amp. type WK welding transformers, high power factor is included as a built-in feature without complicating the design or adding to the weight or price.

High power factor results in low primary current by eliminating most of the out-of-phase or useless current drawn by the transformer. As a result, installation costs are materially reduced because smaller primary cable, fuses, and switches can be used. In many cases, it is possible to connect a new type WK transformer to an existing circuit without overloading it, whereas this would not be possible with similarly rated units having high input current.

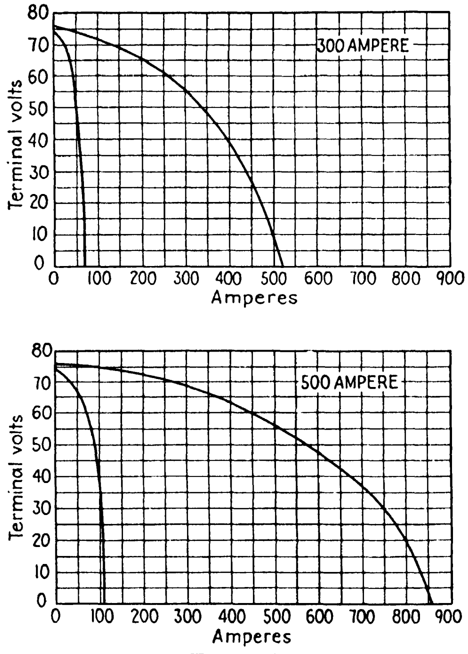


Fig. 138.—Volt-ampere curves, new Type WK arc-welding transformers. (Average values—not guaranteed.) (*Courtesy of General Electric Company.*)

As the 100- and 200-amp. type WK welders use a comparatively small amount of current, power-factor correction usually is not a problem.

Open-circuit Voltage.—Because of the better quality of modern coated electrodes used on a.c. welding, it is no longer necessary to use high open-circuit voltages to ensure arc stability. The new type WK transformers are built with only one open-circuit voltage—75 volts.

Volt-ampere Curves.—The volt-ampere curves on the new type WK welding transformers are shown in Fig. 138. The slope of the curve over the normal range of welding voltages is quite steep, and a change of arc length is thus possible without materially affecting the current drawn. This makes it easy to manipulate the arc.

Duty Cycles.—The fan-cooled design of the new transformers allows operation at high currents and duty cycles on an all-day basis without harmful heating.

Construction—Core and Coils.—Details of core and coil construction are shown in Fig. 139.

The laminated core is composed of high-quality silicon steel which is tightly clamped and bolted to form a rigid support for the coils and case. Because the laminations are firmly held in place over the entire length, vibration and magnetic noise are kept to a minimum. No wooden core wedges, which shrink after considerable use and result in noisy cores, are used.

The transformer coils are made of fiber-glass insulated wire and are firmly held together by fiber-glass tape. The whole coil assembly is thoroughly impregnated with high-temperature insulating varnish to make it rigid and to provide a hard surface which easily radiates heat. Both the primary and secondary coils are wound in several sections to provide ventilating ducts through the center of the coils. Spaced between the coil sections are smooth, asbestos-compound strips which allow free air circulation.

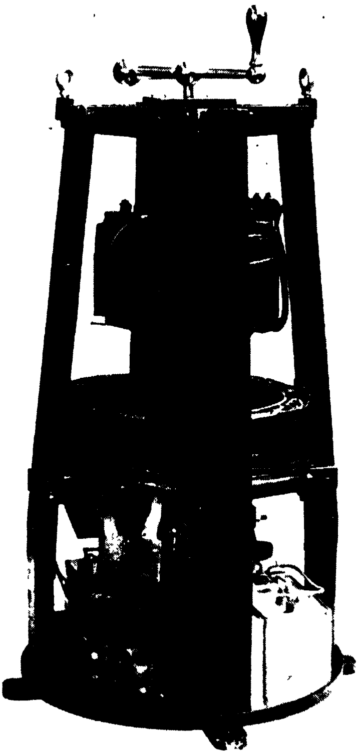


FIG. 139.—Internal view, secondary side, of General Electric arc-welding transformer. (Model 6WK2C1, 60 cycles, 500 amp., 220/440 volts, to 75 volts.) (*Courtesy of General Electric Company.*)

On all type WK transformers the secondary winding is connected to the transformer case at the ground-lead end of the winding. The purpose of this is to limit the voltage that can appear between the ground connection and the electrode holder. With rated voltage on the primary, only the normal open-circuit voltage of the machine can appear, even in the very remote possibility of a breakdown of insulation from coil to coil.

Ventilation.—Circulation of air in the 300- and 500-amp. units is provided by a large completely enclosed fan mounted at the bottom of the transformer case. This fan has ball bearings and has been particularly designed for transformer cooling. The higher air velocity in the fan-cooled units greatly reduces the amount of dust that settles on the windings.

A separate 110-volt winding on the transformer provides power for the totally enclosed fan motor, and no starting switch is required. The fan runs whenever the transformer is energized, and its speed is constant, regardless of the welding load. The fan requires lubrication only once every year or every 18 months. Lubrication fittings on it may be reached through the secondary-lead opening without removing any parts other than the Herkolite cover which is held by four small screws.

Capacitors.—The high power factor of these transformers is obtained by using hermetically sealed Pyranol capacitors which are firmly bolted to the transformer base where they are thoroughly protected by the transformer case. They are permanently connected across the 440-volt section at the primary winding so that they operate at full voltage and kva. regardless of whether the transformer is operated on 220, 440, or 550 volts. Four capacitors are used on the 300-amp. size and seven on the 500.

The life of the capacitors should be as long as that of the transformer. The General Electric Company has over 400,000 kva. of Pyranol capacitors installed, and their service record is over 99.8 per cent perfect.

Current-adjusting Mechanism.—The extremely simple current-adjusting mechanism consists of a single threaded shaft which moves a bronze carrier that supports the movable primary coil. Three grease-gun fittings are provided on the transformer cover for lubricating the bearings and guides. No gears, heavy springs, or rubber vibration-absorbing parts are used. Because of the simplicity of the mechanism and the fact that only a relatively lightweight primary coil must be moved to vary the current, "finger-tip" control is provided.

Current Indicator.—The large, easily read current indicator is shown in Fig. 133. The scale is spread out so that it is possible easily and accurately to set the welding current desired on the first try and even to minimize voltage fluctuations on weak, overloaded feeders by reducing primary current and improving power factor, more accurate current indication being thus ensured.

A glance at the transformer indicates the current and eliminates the need of walking to the transformer to read indicators or instruments that may be inaccurate or difficult to see. Although instruments are considered unnecessary on these transformers, provision has been made for easily and quickly mounting an ammeter when desired. This may be done without drilling any holes or using any special tools. An ammeter can be provided mounted in a sheet-steel hood which may be bolted on the transformer with the same four bolts that hold the small GE monogram plate just above the name plate. A built-in current transformer is provided in every 300- and 500-amp. new type WK welding transformer so that all that is necessary is to connect the ammeter to the two leads from the current transformer.

Lead Length.—With closely spaced leads, the rated output of the transformers can be obtained with leads each 100 ft. long. With longer leads, the maximum output will be only slightly reduced.

Parallel Operation.—These transformers will operate successfully in parallel with other arc-welding transformers having the same primary-voltage rating and having a secondary open-circuit-voltage rating within 10 volts of the secondary rating of these transformers. Primary leads must be connected to the same phase and in correct polarity. They must be solidly connected together without intervening switches or fuses.

If one transformer having its primary disconnected should be excited from another transformer through its secondary winding, the primary capacitors may be damaged by the current supplied to them through the high reactance of the transformers. For the same reason, this transformer should not be used as a step-up transformer or excited from its secondary terminals unless capacitors are disconnected from the primary.

To check the polarity of transformers for parallel connections, the welding ground-lead terminals should first be connected together. The primaries should then be connected to the same phase of the power supply. Before connecting the welding leads together, an a.c. voltmeter (reading at least 100 volts) should be connected across the two welding lead terminals. If the voltmeter shows a low voltage (less than 15 volts), the polarity is correct, and the welding leads may be paralleled. If the voltmeter reads high, the polarity is wrong and the primary connections of one transformer to the power supply should be reversed. The same voltmeter check should again be made before the welding leads are paralleled. (NOTE: An ordinary 110-volt lamp may be flashed across the welding leads in lieu of a voltmeter. If it does not light, the polarity is correct. If it lights brightly, the polarity is wrong.)

ELECTRODES

Metallic Electrodes.—In metallic-arc welding, the material to be welded is usually a ferrous alloy, such as cast iron, rolled steel, cast steel, chrome steel, chrome-nickel steel, manganese steel, and many others, or a nonferrous alloy, such as bronze, brass, and so forth. Of course, there are other metals that are welded almost in their pure state, such as aluminum.

The various elements react differently under the influence of the heat of the arc, and electrodes of suitable characteristics are required. When heated, some metals expand more than others, and some oxidize more rapidly than others. Since the metal being welded may have a different coefficient of expansion than that of the deposited metal, it is possible that undue stresses and even cracking of the weld may occur. It is therefore necessary that electrodes be suited to meet such conditions.

Metallic electrodes are generally used in hand welding. They are commercially manufactured in diameter sizes ranging from 1/16 to 3/8 in. and usually in lengths of 14 to 18 in. The proper size of electrode to be used depends upon the requirements of the weld and the material to be welded. The type of work and the composition of material to be welded determine the composition of the electrode.

There are several types of electrodes in common use, among which are bare electrodes, dust- and lightly coated electrodes, medium-, or semi-coated, electrodes, and heavily coated electrodes.

The term *bare electrode*, as used in the arc-welding industry, has come to have a double meaning. During the early days of arc welding, electrodes were nothing else but ordinary fence wire and, as such, were properly known as "bare welding wire." Because of the very poor results obtained with such wire, improvements were soon made to avoid difficulties. Nowadays, only steel of a definite chemical analysis is used in drawing electrode wire to uniform size. In some cases, after the wire is drawn a thin coating is applied over it. In other cases, the coating or processing is done before the wire is drawn to its final size; and since it has somewhat the same appearance as the really bare fence wire used years ago, the wire is still called bare.

The *dust-coated* and *lightly coated electrodes*, are those which are lightly coated with an arc-stabilizing chemical. They may have a light coating of lime upon them, retained from the lubricant in the drawing process; or they may be of the sul-coated type, which are lightly rusted and then drawn and when used have a smooth surface and a deep rust color. The coating does not affect the characteristics of the deposited weld metal but serves only to produce electrodes of more uniform arc characteristics than bare welding wire. There is no attempt made to prevent oxidation, and there is no slag formed on the bead.

Medium-, or *semi-coated, electrodes* are those which have a coating of appreciable thickness. The coating serves not only to stabilize the arc but also partly to control the oxidation of the molten metal, as it is deposited, by forming a thin film of slag over the surface of the bead. The coating amounts to about 1 or 2 per cent of the total weight of the electrode.

Heavily coated electrodes make use of all the benefits of chemical coatings. These coatings, which in weight may amount to 10 per cent or more of the total weight of the electrode, make possible the control of the arc characteristics and of the physical and chemical properties of the deposited metal.

The electrode coating is consumed in the arc at a slower rate than the metal core of the electrode. As a result, the coating extends beyond the metal core and serves to direct and concentrate the arc stream, to reduce thermal losses, and to increase the temperature of the electrode tip. This, of course, increases the rate of deposition as well as the penetration of the weld metal. The extent of the sheath depends upon the refractoriness and the thickness of the coating (see Fig. 140).

In the heat of the arc, the heavy coating gives off large quantities of gas which envelops and completely shields the arc and metal from the surrounding atmosphere. The gaseous envelope is produced by the volatilization, dissociation, and combustion of the organic materials of which the coatings are generally made and thus consists chiefly of hydrogen and carbon monoxide. These gases burn to carbon dioxide and water vapor at the outer portions of the arc where oxygen is available. From the standpoint of shielding, the gases function by excluding air and consuming oxygen. If combustible materials are not used in the coating, the arc is shielded by vaporized metallic oxides and silicates.

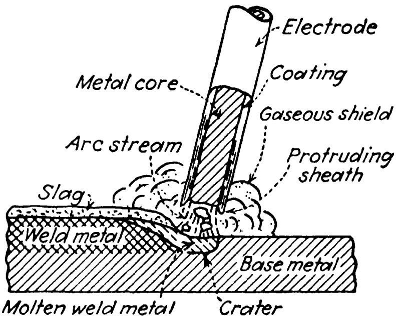


FIG. 140.—Metallic shielded arc with gas and slag producing coating.

The action of the arc on the coating results in a slag formation which floats on top of the molten weld metal and thus functions as an insulation against the air while cooling. The slag is produced by the melting and reaction of the less volatile mineral ingredients of the coating and may easily be removed after the weld metal is sufficiently cooled.

Acting as a scavenger, the molten slag, in contact with the molten weld metal, removes oxides and other impurities from the weld. The fluidity of the metal is increased, and thus the latter flows more smoothly and uniformly.

Since coatings are usually very poor conductors of electricity, they permit the use of covered electrodes in narrow grooves and close quarters without short-circuiting the current by contact of the sides of the electrode against the work.

The coating is an excellent medium for introducing into the weld metal various alloying elements for the production of tensile strength, hardness, corrosion resistance, or other physical properties. To eliminate small amounts of oxygen that may have reacted with the weld metal and to control the desired amounts of alloying elements, metallic deoxidizers are usually added to the coating. Now and then, they are added to compensate for oxygen that is liberated from certain coating ingredients.

The coatings usually contain compounds of substances such as silicon, barium, calcium, and magnesium. Water glass, a solution of sodium silicates, is generally used as a builder; but various gums, glues, and lacquers are also used.

Each manufacturer develops his own specific manufacturing process, but the coating is commonly applied to the wire by one of the following processes:

1. Single or multiple dip of metallic rod into a flux paste.
2. Extrusion of a doughlike consistency of flux onto the metallic rod.
3. Application of a woven-fabric sleeve impregnated with flux material.
4. Application of an open-spiral winding of asbestos or cotton and extrusion of a thick flux paste, completely filling and covering this spiral.
5. Sheathing a flux-covered wire with paper or other tape or a metallic strip.
6. Application of a woven-wire mesh to the core wire and extrusion of a flux to fill the mesh, the top of the wire being left exposed.

Subsequent drying or baking of the electrodes is necessary to eliminate the moisture from the flux.

In selecting electrodes for a job, to get best results and economy, each application should be carefully analyzed on the basis of the results desired and selection of the best type of electrode made accordingly.

Carbon Electrodes.—Rods of carbon or graphite are used as electrodes for carbon-arc welding and cutting.

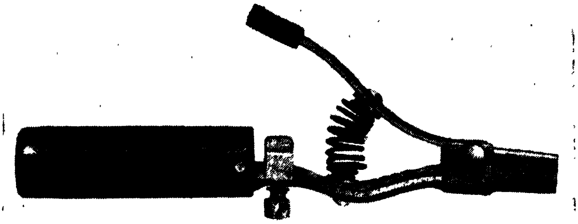
Carbon electrodes are manufactured in diameter sizes ranging from $5/32$ in. up to and including 1 in., in 12-in. lengths. The carbons are baked in the process of manufacture.

The electrodes should be of uniform structure and as free as possible from impurities. For welding purposes, graphite electrodes yield longer life than hard-carbon electrodes. The carbon electrode has greater strength, but the graphite electrode has lower resistance and thus is capable of conducting more current.

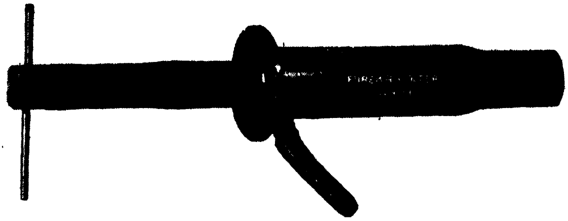
ELECTRODE HOLDERS

An electrode holder is a clamping device for holding the electrode. It is equipped with a handle for the operator's hand, and the welding current is conveyed through it to the electrode (see Fig. 141).

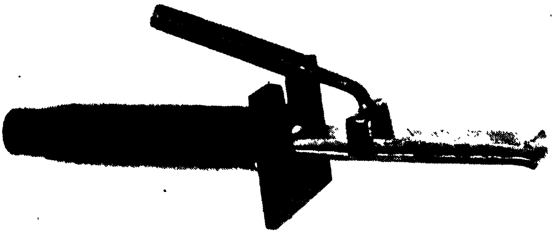
The electrode holder should hold the electrode securely in position and yet permit quick and easy change of electrodes while providing good electrical contact; it should be of sufficient size to accommodate all sizes of electrodes that are likely to be used; the current-carrying parts must be sufficiently large to prevent the handle from becoming uncomfortably warm, and the handle should be insulated from the heat and from the



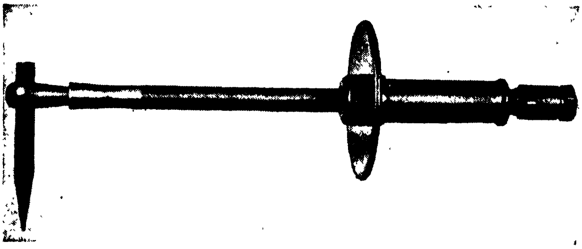
"Lincoln" type. (*Courtesy of The Lincoln Electric Company.*)



'Eureka" type. (*Courtesy of The Fibre-Metal Products Company.*)



"Duro" type. (*Courtesy of General Electric Company.*)



"Vulcan" type. (*Courtesy of The Fibre-Metal Products Company.*)
Fig. 141.—Types of electrode holders.

current-carrying parts. The holder should be light in weight and balanced and should have a comfortable grip to permit ease of handling; yet it should be sturdy enough to withstand rough usage.

It is very important that the first 5 to 15 ft. of cable attached to the holder be very flexible, to prevent the operator's becoming unnecessarily tired in manipulating the electrode.

CABLES AND CABLE CONNECTIONS

Welding Cables or Leads.—Two cables of adequate current-carrying capacity are required to complete the electric circuit between the welding machine and the work—an electrode cable and a ground cable. As pointed out before, an extra flexible cable is used between the electrode holder and the welding machine. If a long electrode cable is required, it may be entirely of the very flexible type, or it may be spliced to the machine with an extension of less flexible cable.

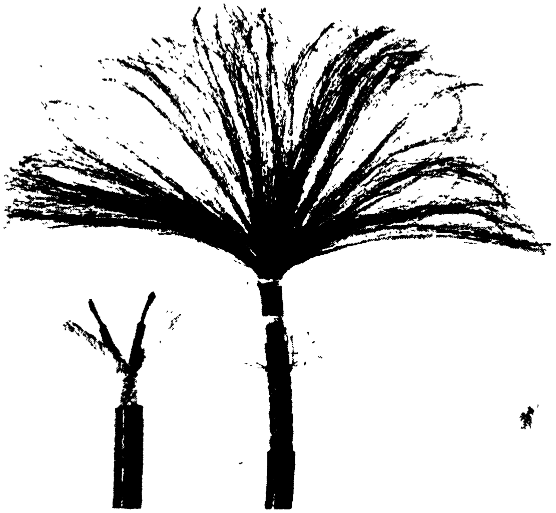


FIG. 142.—Typical construction of arc-welding cable. (*Courtesy of The Lincoln Electric Company.*)

The electrode cable, designed expressly for welding service, derives its high flexibility from its construction. It may be woven of thousands of very fine, almost hairlike strands of copper wire enclosed in a durable wrapping, usually paper, which allows the conductor to slip readily within its rubber insulation when the cable is bent. The insulation should be for sufficiently high voltage, and the jacket should be tough and flexible to resist abrasion and heat (see Fig. 142).

Since the work forms a part of the electric circuit in arc welding, an electric conductor of adequate capacity must be provided between the work and the ground terminal of the welding machine. Usually, a cable of the same size as the electrode cable is employed, but it does not need to be unusually flexible, although such cable can be used.

The size of the cable used in welding is dependent upon the capacity of the machine and the distance of the work from the machine. It should be carefully selected because of its definite bearing on weld production and efficiency. The following table indicates cable sizes for various lengths for welding machines of different sizes.

TABLE II.—CABLE SIZES

Machine size, amp.	Cable sizes for lengths		
	Up to 50 ft.	50–100 ft.	100–250 ft.
100	2	2	2
200	2	1	2/0
300	0	2/0	4/0
400	2/0	3/0	4/0*
600	2/0	4/0	4/0*

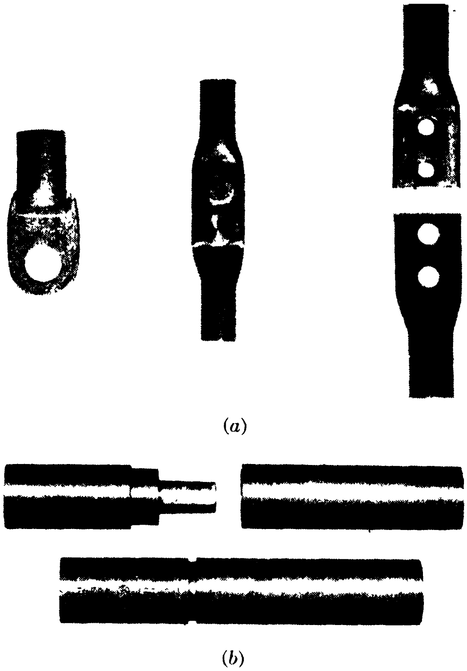
* The greatest length of 4/0 cable recommended for a 400-amp. welder is 150 ft.; for a 600-amp. machine 100 ft. For greater distances, cable size is increased. The question of the longest cable practical to use is determined by considering the weld production, efficiency, and ease of handling.

Wherever it is undesirable to move the equipment around or where the work cannot be brought to the welding bench because of its size, the usual practice is to have long cables available to reach the work. In some shops, the generator is grounded to the steel framework of the building; or, in the case of concrete structures, a permanent ground is run to various parts of the building. This necessitates only the running of the electrode cable to the location of the work.

However, welding cables that are too long may result in a voltage drop so great as to affect the amount of useful energy transmitted to the welding arc. For this reason, it is always most desirable to have the machine located as near to the work as possible.

If a checkup on the voltage drop of the cables is desired, a method similar to the following can be used: (1) The electrode holder should be short-circuited at the point where the welding is to be done. (2) The rheostat on the generator should be set to give a definite amperage. (3) The voltmeter on the panel should be read for the voltage; or if an additional voltmeter is available, the voltage drop should be measured at the switch. This will give the total voltage drop on cables going and returning. The size of the copper wire being known, the voltage drop can easily be calculated; and if it does not agree with that tabulated in Standard Wire Tables, then loose connections in the entire welding circuit should be looked for.

If another voltmeter is not available, the machine should be short-circuited at the outgoing terminals of the switch, the rheostat should be adjusted to definite amperage, and the voltage should be noted. The electrode holder should then be short-circuited on work at the distant point, the machine being adjusted to the same amperage. The voltage should then be read again. The difference between the second and the first voltage readings represents the true voltage drop of cables. For best results, the voltage drop across the cables should not be over 10 volts. If it is, then a larger cable should be used.



(a)

(b)

Fig. 143.—Cable connectors. (*Courtesy of The Lincoln Electric Company and General Electric Company.*)

To reduce voltage losses, with a.c. welding especially, if long leads are used, both the ground lead and the electrode lead should be physically as close together as possible.

Welding-cable Connections.—Suitable lugs should be used for connecting both the electrode cable and the ground cable to the arc welder; in addition, the ground cable should be provided with a convenient means for connecting it to the work. This connection may consist of a copper hook securely fastened to the lead and hung on a part of the work; or it may be simply a heavy weight to which the ground lead is securely fastened, the weight being merely laid on top of the work. If the setup permits it, the ground cable is often bolted to a steel plate on which the work rests, or it may be fastened to the metal framework of a building from which the operator may wish to take off his ground to the work at some distant point.

Perhaps the best method of connecting the ground cable to the work is by means of a steel plate bolted to the cable. To ensure a tight connection, the plate can easily be tack-welded or clamped to the work. In working on a bench that is properly constructed and kept clean, the ground plate can be connected to the bench, and the work is thus grounded when laid on the bench.

All connections should be made tight and should be properly taped. With loose connections, the lugs will become heated, the solder will be loosened, and the connections will break.

Power Cable.—Conductors of ample capacity and adequately insulated for the voltage are used to transmit the power to welding machines from the electric power line. If the machine is of the stationary type, the wiring must conform to the National Electrical Code (N.E.C.); if portable, portable cable is ordinarily used.

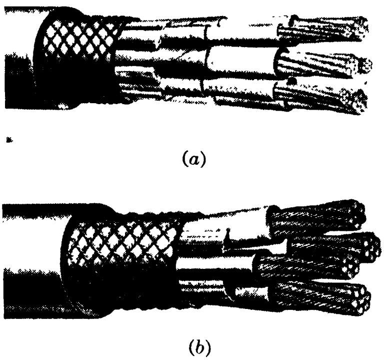


Fig. 144.—Typical construction of portable power cables. (*Courtesy of General Electric Company.*)

To prevent an electric shock in case of injury to insulation of either cable or machine, the frame of the arc-welding machine is grounded by using a portable cable with an extra conductor. The extra conductor, acting as the grounding medium, is fastened to the frame of the welder on one end and to a solid ground on the other.

The voltage on the power side of a welding machine is usually much greater than that on the output side; therefore, it is important that the portable power cable is properly and adequately insulated with tough abrasive-resisting insulation in order to stand up under the rough usage it ordinarily undergoes.

PROTECTIVE EQUIPMENT

It is part of the welding operator's business to know not only the hazards that might arise in arc welding but also how to take the proper protective measures.

Head and Hand Shields.—The light or rays from the welding arc consist of ultraviolet rays, visible rays, and infrared rays. It is necessary that the operator's eyes and skin be protected from these rays, direct or reflected. If this is not done, there is danger of what is commonly known as "flashes" or "hot sand in the eyes," which does not result in permanent injury to the eyes but which is extremely painful while it lasts. The skin is affected in a manner similar to a severe case of sunburn. The rays may burn the eyes at any distance within 40 ft. and the skin at any distance within 20 ft. Various types of shield are available for protecting the head, eyes, face, and neck (see Fig. 145).

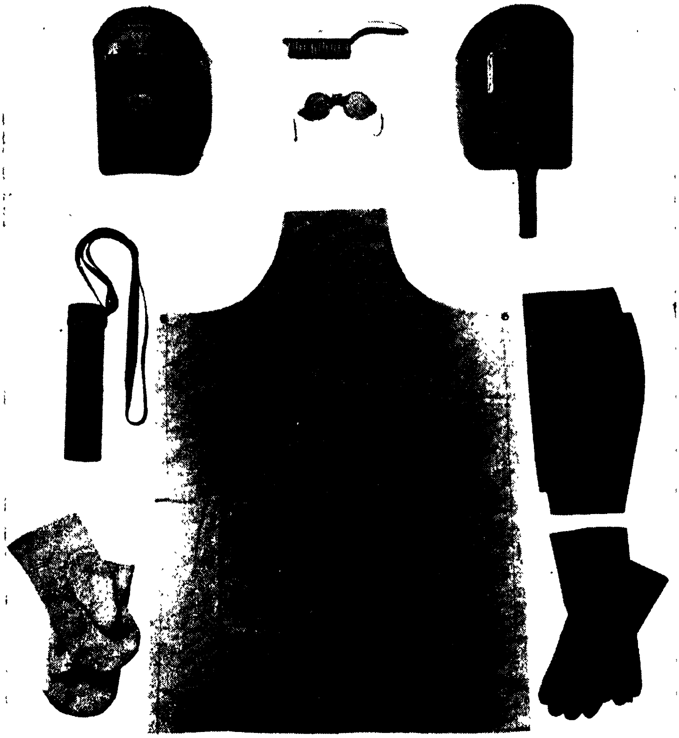


FIG. 145.—Typical arc-welding accessories; illustrating welder's helmet, handshield, goggles, wire brush, electrode carrier, asbestos mitts, sleeve protectors, leather gloves, and fire-proofed apron. (*Courtesy of General Electric Company.*)

The hand, or face, shield is provided with a handle which is held by the operator, who has thus only one hand free to manipulate the torch. The head shield, often known as a "hood" or "helmet," is worn like a helmet, and both hands are left free to manipulate the torch and to hold work in position, if this is desirable. It is made so that it can be swung up over the head without entirely removing it from the head; the operator thus has good visibility when not welding. The choice between the two types depends upon the operator's personal preference and upon the type of work being done.

Both types of shield are usually constructed of some kind of pressed-fiber insulating material, dead black in color to reduce reflection. They are light in weight and are designed to ensure the greatest possible comfort and protection to the welder or user.

They are provided with a colored-glass window, or welding lens, the standard size of which is 2 × 4½ in. The colored glass should be of such composition as to absorb or screen out the ultraviolet rays, the infrared rays, and most of the visible rays emanating from the arc (see Fig. 146). The density of the color chosen is dependent upon the brightness of the arc employed, and this in turn is governed by the amount of current used. Lenses supplied by reputable manufacturers can safely be used. As a matter of fact, some lenses are guaranteed to absorb 99.5 per cent or more of the infrared rays and 99.75 per cent or more of the ultraviolet rays present.

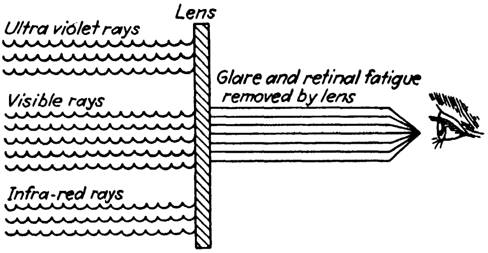


FIG. 146.—Filtering of rays in electric arc by welding lens.

A chemically treated, clear, "nonsplatter" glass is usually placed on the exposed side of the lens to protect it from molten-metal splatter and breakage.

Special goggles are generally worn by those working close to a welding arc to protect their eyes from occasional flashes. The goggles are usually provided with an adjustable elastic headband and are light, cool, well ventilated, and comfortable. Like shields, they are provided with colored and clear lenses.

If the eyes become burned for any reason, the intense pain may last for as long as 24 to 48 hr. Immediate relief may be obtained by placing a drop of 2 per cent Butyn solution in the burned eye. It has an anesthetic effect and lasts for about 2 hr. Two applications are usually sufficient. Treating the eye with sweet oil once an hour until burning disappears is also satisfactory. An application of boric acid is also helpful. A solution of 5 to 10 per cent Argyrol is very often used to aid healing but should not be applied more than once every 5 hr.

Gloves.—Gauntlet-type gloves are generally worn by welding operators to protect the hands from the arc rays, splatter of molten metal, sparks, and so on (see Fig. 145). They should preferably be made of flexible leather, but they should not be so thin as to shrivel, wrinkle up, or burn through easily. Woven-asbestos gloves are also very good. Cotton gloves offer only temporary protection, for the splatter of metal burns holes through them very easily.

Aprons and Other Clothing.—During the actual welding operation, the continuous shower of sparks and globules of molten metal thrown out by the arc may result in severe burns. As a protection, especially when the operator is sitting down, it is advisable to wear an apron of leather, asbestos, or some other type of fire-resisting protective fabric. Some operators also like to wear sleevelets of like material (see Fig. 145).

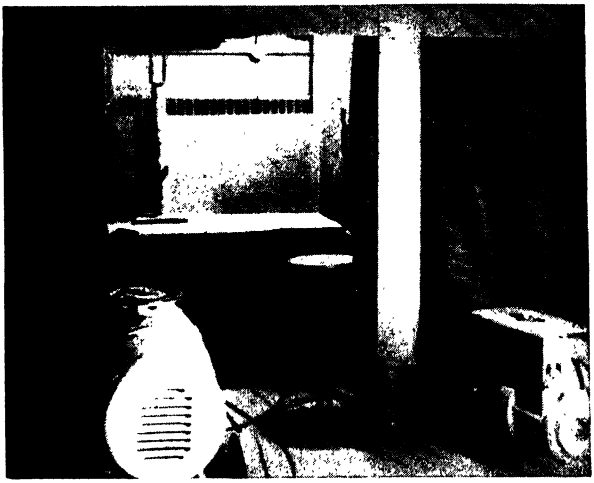


FIG. 147.—Typical arc-welding booth. (*Courtesy of The Delehanty Institute.*)

To prevent globules of molten metal from falling into the shoes and causing a small but painful and slow-healing burn to the foot before it can be extracted from the shoe, it is advisable to have some sort of protection for the operator's ankles and feet, such as leggings or spats. A good precaution is to wear cuffless trousers and to hold the ends of the trouser legs over the shoe tops by means of bicycle clips.

Screens and Booths.—Besides protecting the operator, it is essential to provide suitable protection for others who may be working or passing near the location where the arc welding is in operation.

In some cases, it is possible to have the welding done in enclosed booths, but in others the machine must be taken to the work. In the latter instance, it is advisable to surround the scene of welding operation with portable screens. These may be constructed of pipes, angle irons, wood, sheet metal, or heavy canvas and should be painted or sprayed with ultraviolet protective paint to prevent reflection of the arc rays.

Zinc oxide paint answers this purpose most satisfactorily and is usually colored a deep gray with lampblack. A dead-black color is also used. The dried surface should be flat and should have no gloss.

As an added precaution, danger signs may be posted near the scene of the welding operation to warn against looking at the arc with unprotected eyes.

Ventilation.—In a well-ventilated welding shop, the fumes given off by welding processes may not be harmful; but if the shop is closed in and is not properly ventilated, care should be taken to provide some means of drawing the fumes outside the building.

At times, if the operator is working in confined spaces and if the fumes given off by the base metal or filler rod are of the poisonous type, it may be necessary to equip him with mask provided with air from outside sources.

MISCELLANEOUS ACCESSORIES

Welding Table.—A steel table or bench is very useful for the positioning of small work that may be moved about by hand. Also, many jobs consist of angle-iron frames, flat pieces, and so forth; in such cases, it is advantageous to have a flat surface on which to lay out the job.

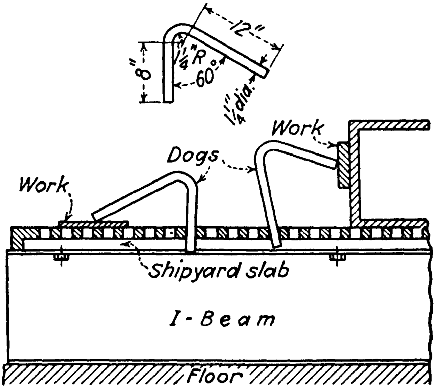


Fig. 148.—Detail of dogs for shipyard slab and typical application.

The table may consist of a steel plate set upon some type of framework, and its height may vary from 30 to 36 in.

Often, the ground-cable connection is securely attached to the table top, and the work to be welded is laid on the table, the contact made being usually sufficient to carry the necessary welding current. To facilitate the clamping of the work in position, the table top may be provided with slots or holes. A suitable container for electrodes and a well-insulated retainer for the electrode holder may also be added.

Welding Slabs, Fixtures, and Manipulators.—For shopwork, the shipyard type of slab and dog has been found preferable to any type of machine-shop slab using bolts (see Fig. 148). For repetitive work and for work requiring considerable accuracy, jigs, fixtures, and manipulators are often very valuable. They permit the placing of the product in the most suitable welding position, and thus the welds can be made at higher production rates, without suffering in quality (see Chap. XII).

Electrode Receptacles.—To prevent the littering of shop floors with electrodes and stubs, each operator should be provided with a suitably designed receptacle. At the start of the day's work, the receptacle should be emptied of stubs and supplied with electrodes. Leather tubular receptacles with a strap for attachment to a belt are suitable where portability is wanted (see Fig. 145).

Cleaning Accessories.—In welding, cleanliness of the work is of the utmost importance. To prevent undue contamination and subsequent weakening of the joint because of brittleness and possible gas pockets, the surfaces of the joint to be welded should be cleaned of rust, oil, and other foreign material. For the same reason, passes on multiple-pass joints should be thoroughly cleaned. Cleanliness after the joint has been welded is equally important for the sake of appearance, especially if the surface is to be painted or otherwise finished.

Steel-wire scratch brushes, chisels, and peening hammers are the tools ordinarily employed for cleaning slag, scale, rust, or other dry material. These tools may be either hand- or power-operated.

Gasoline, caustic soda, and pickling acid may be used for removing grease and oil, as well as scale; but the surface should be well dried before welding is begun, for the vapors given off may interfere with the arc. Of course, extreme care should be taken to avoid fire in using gasoline or any other inflammable material.

To prevent the adhesion of weld splatter, the surface adjacent to the joint may be sprayed or painted with a coating material. This coating material should not cause brittleness or porosity in the deposited metal, should cause no injurious fumes, should withstand preheating temperatures ordinarily required, should not cause corrosion of the base metal, and preferably should not require removal afterward.

Preheating and Annealing Equipment.—There is little or no use for preheating on the average job done by the arc-welding process. Preheating, however, is desirable in some cases such as for very large gray-iron castings. When preheating or annealing is necessary, it is done in some kind of oven or furnace. If the work is sufficient to warrant the installation, permanent ovens are used; otherwise, temporary enclosures built of ordinary brick without cement are used. The necessary heat may be supplied by gas or oil burners, coke and coal fires, or electric space heaters. With burners, the flame should not play directly on the part being heated.

Backing Equipment.—Backing is especially helpful to prevent molten metal from running through the joint being welded, especially when lighter gauges are being welded. It also aids in preventing very light metal, especially of low melting point, such as aluminum, from melting away.

Steel and copper blocks, strips, and bars, carbon blocks, firebricks, plastic asbestos, fire clay, and a mixture of sodium silicate (water glass) with carbon powder are all used for backing openings, to conduct heat away, and for building molds or dams of special shape when required.

Copper is most satisfactory because of its high heat conductivity and because it is not so likely to fuse in the weld.

Cooling Equipment.—When slow cooling is desired, the welded work may be covered with dry sand. Small objects are successfully and slowly cooled by burying them in powdered asbestos or flake mica. Large work is sometimes thoroughly wrapped in asbestos paper to retard the cooling process.

Miscellaneous Equipment.—Many tools for the handling and positioning of work are used in welding shops, especially when job welding is done. Among them will be found chain hoists, cranes, jacks, C clamps, tongs of various kinds, pliers, and the like. Wedges of all sizes are used for spacing and lining up parts. Sandblasting outfits, portable drills, and grinders are widely used to finish off the surface of welds, to prepare joints for welding, to remove scale and hard metal, and so on. Water-soaked waste may be used to prevent the heat from spreading too far into the work piece. Soapstone crayon is well suited for marking on metal, cold or hot.

Welding Operator's Tool Kit.—An ideal tool kit for the welding operator should contain the following items: identification stamp, fillet-weld gauges, ball peen hammer, spirit level, plumb bob, combination square, flexible steel rule, several flat and gouge chisels, lightweight slag hammer, stiff scratch wire brush, center punch, scriber, and stick of soapstone.

CARE OF EQUIPMENT

As is true of any other type of equipment, the condition in which the welding equipment is kept determines to a great extent the results that will be obtained.

The welder should be inspected regularly and kept in efficient operating condition. Also, it should be protected from dirt, dust, and harmful fumes. The welding table and floor should be kept clean, for dirt and foreign matter getting into the weld can ruin it. Tools and other objects should not be left lying around, for they may thus be the cause of serious injury to the operator as he goes about his work.

Efficient industrial plants place a great deal of emphasis on cleanliness and order, and the welding shop should give special consideration to these factors.

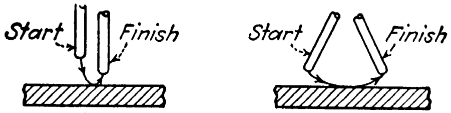
CHAPTER VII

TECHNIQUE OF ARC WELDING

MANIPULATION OF THE ARC AND ITS REQUIREMENTS[1]

The manipulation of the welding arc may be properly learned by anyone having average intelligence and a steady hand. Previous mechanical training will help the prospective welding operator to become proficient but is not essential. A full understanding of the requirements of the welding arc will prove an invaluable aid.

Gripping the Electrode.—In the manual metallic-arc-welding process, it is desirable to grip the electrode at the end remote from the arc terminal so that the entire length can be deposited without breaking the arc. But sometimes, to avoid overheating, very small electrodes and coated electrodes of extra length are provided with an exposed section in the center for the electrode-holder grip.



(a)-Vertical method *(b)*-Scratch method

FIG. 149.—Striking the arc.

In the automatic metallic-arc-welding process, an endeavor is made to conduct the current to the electrode as near as is practical to its arc terminal, the welding current and the welding speed being thus increased by localizing the heating of the electrode within a very short length.

Carbon electrodes are usually gripped between the ends or at the end adjacent to the arc terminal, so as to prevent the overheating of the entire electrode.

Striking the Arc.—To strike a metallic or carbon arc, the work is touched with the electrode, and the latter is quickly withdrawn an amount not exceeding that required to maintain the arc under welding conditions (see Fig. 149*a*).

When a metallic arc is struck, there is a tendency for the electrode to "freeze," or stick, to the work because of the sudden rush of current induced by the short-circuiting of the machine. In manual bare-electrode welding, this tendency is very pronounced; therefore, it is desirable to employ a lateral motion to strike the arc similar to that of striking a match (see Fig. 149*b*)

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[1] Part of the material in this chapter has been condensed from Chap. III of the "Welding Handbook" of the A.W.S.

In striking the arc with some types of coated electrode, it is necessary forcibly to remove the projecting covering on the electrode tip by tapping it on the work.

When a carbon arc is struck, care should be taken to avoid striking it in a molten crater, for particles of slag may adhere to the electrode and cause an irregularly shaped arc. Also the dipping of the hot carbon electrode into the puddle of molten metal may result in sufficient carbon being transferred into the molten metal to carbonize it.

Maintaining the Arc.—A metallic arc, after it has been struck, is maintained by a uniform continuous movement of the electrode toward the work to compensate progressively for that portion which has been melted and deposited in the weld. At the same time, the electrode is also progressively advanced or moved in the direction of welding.

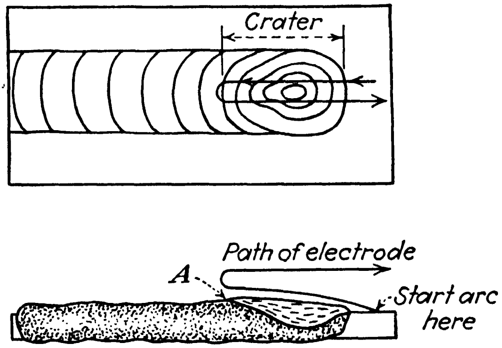
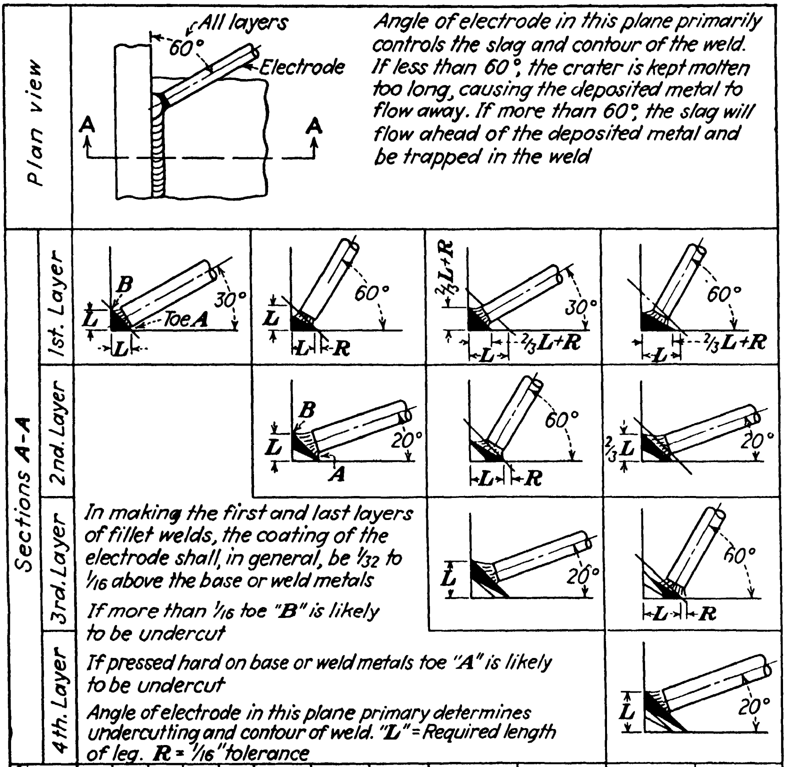


FIG. 150.—Restriking the arc when broken while welding.

Breaking the Arc.—There are two procedures for breaking the arc. (1) The arc is shortened, and the electrode is moved quickly sideways out of the crater. This procedure is used in manual welding when electrodes are changed and the weld is to be continued from the same crater. (2) The electrode is held stationary long enough to fill the crater and then is gradually withdrawn. This method is used in manual and automatic welding when it is desired to minimize or to eliminate the crater.

Restriking the Arc to Continue the Weld.—In restriking the arc in the crater, the arc should be struck at the forward, or cold, end of the crater and moved backward over the crater and then forward again to continue the weld. By this procedure the crater becomes filled and porosity and trapping of the slag are avoided (see Fig. 150).

Angularity of Electrode to Work.—The quality of the weld metal may be determined to a marked degree by the angular deposition of the electrode to the work. Upon the latter may depend the freedom from undercutting and slag inclusion, the ease with which the filler metal is placed in the weld, the uniformity of fusion, and the weld contour as affected by the influence of surface tension and gravity of the molten metal (see Fig. 151).



Angle of electrode in this plane primarily controls the slag and contour of the weld. If less than 60°, the crater is kept molten too long, causing the deposited metal to flow away. If more than 60°, the slag will flow ahead of the deposited metal and be trapped in the weld

In making the first and last layers of fillet welds, the coating of the electrode shall, in general, be 1/32 to 1/16 above the base or weld metals

If more than 1/16 toe "B" is likely to be undercut

If pressed hard on base or weld metals toe "A" is likely to be undercut

Angle of electrode in this plane primary determines undercutting and contour of weld. "L" = Required length of leg. R = 1/16" tolerance

Size of weld	1/8	3/16	1/4	5/16	5/8	1/4	5/16	3/8	7/16	1/2	7/16	1/2
Size of electrode	3/32	1/8	3/16	3/16	1/4	5/32	3/16	3/16	1/4	1/4	3/16	3/16
No. of layers	One					Two			Three		Four	

Fig. 151.—Deposition technique for standard 45 deg. covered electrode fillet welds.

Weaving the Electrode.—In depositing weld metal, it is often desirable to make the width of the deposit wider than that obtained by a string bead. In such cases a weaving motion is applied to the electrode as it is advanced along the line of weld (see Fig. 152). By weaving, it is possible to deposit more metal at a single pass, not only in welding in a Vee groove on heavy plates, but also in making a fillet weld or in building up a pad.

There are a number of different weaving motions used in welding, but in all cases it is important that the motion be uniform. If the weave used is not uniform or close enough, there is danger of poor fusion at the edges of the deposit (see Fig. 153).

Polarity.—The term *polarity* in welding may be attributed to the fact that every electrical circuit has a negative and a positive terminal or pole.

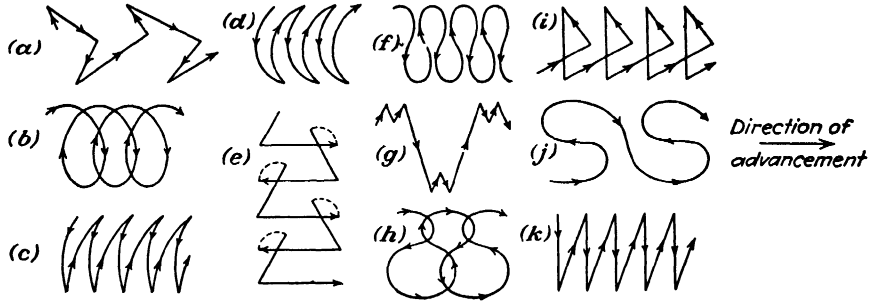


Fig. 152.—Typical weaving motions.

In a d.c. circuit, the current flows in one direction only. The line that carries current from the supply is called the "positive" side; the line that returns the current to the supply is called the "negative" side. It is believed that approximately 60 to 75 per cent of the heat is liberated at the positive side of the circuit and 40 to 25 per cent at the negative side. Since the mass of the work to be welded is usually larger than the mass of the electrode, it is desirable to have more heat liberated in the work than in the electrode, so that both may reach the fusing point at the same time. Therefore, in d.c. welding with bare or lightly coated steel electrodes, the workpiece is usually connected to the positive side of the circuit and the electrode is attached to the negative side. The condition is referred to as *straight polarity* (see Fig. 154).

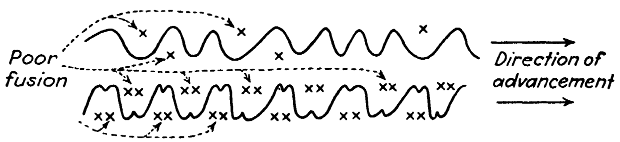


Fig. 153.—Result of beads' not being uniform or close enough.

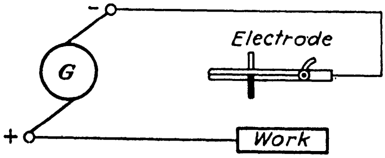


Fig. 154.—Connections for straight polarity.

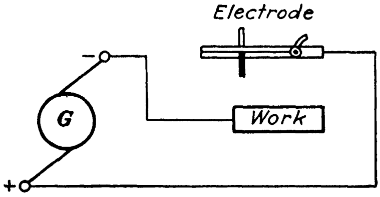


Fig. 155.—Connections for reversed polarity.

However, in some cases, such as in joining thin material, in welding cast iron, and in using certain types of heavily coated ferrous and nonferrous electrodes, the work is made negative and the electrode positive. This condition is known as *reversed polarity* (see Fig. 155).

With the carbon electrode, straight polarity should always be used. With reversed polarity, the arc is extremely unstable, and particles of carbon are deposited on the work. Also, there is a good possibility of the carbon monoxide given off by the electrode coming in contact with the molten metal, being absorbed, and thus carbonizing the base metal and making it hard. This is especially true in the welding of steel.

In using a.c. welding machines, no choice of polarity is made, for it is the characteristic of alternating current to change its polarity many times a second. For this reason, it is not possible to use a.c. machines for all types of welding. For instance, alternating current cannot be used for bare-electrode welding and is rather difficult to use for carbon-arc welding.

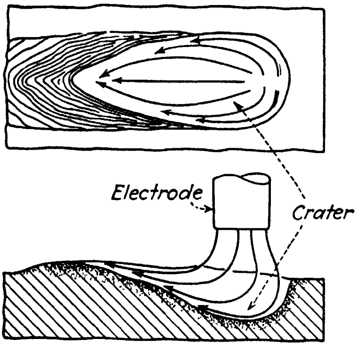


Fig. 156.—Diagram showing flow of metal when welding.

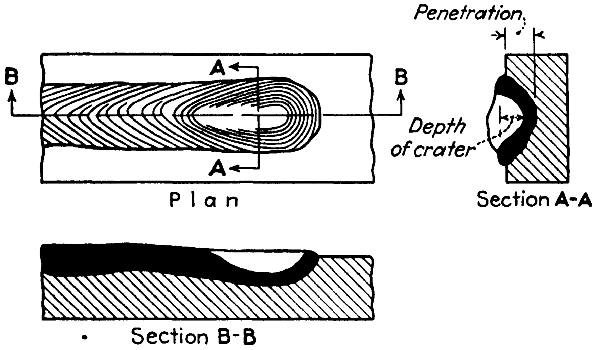
To facilitate the reversing of the polarity of the electrodes, most modern machines are provided with a reverse polarity switch. If a machine is not so equipped, then the welding cables on the terminal lugs of the generator must of necessity be reversed. This means that the electrode-holder cable would be attached where the ground cable was originally and that the ground cable would be connected where the electrode-holder cable originally was.

If no other means are available, the existing polarity hookup of a welder can easily be determined by striking an arc with a carbon electrode. If the arc is easily maintained when drawn away from the work, the hookup is that of straight polarity; if the arc breaks and is difficult to maintain, then the hookup is that of reversed polarity.

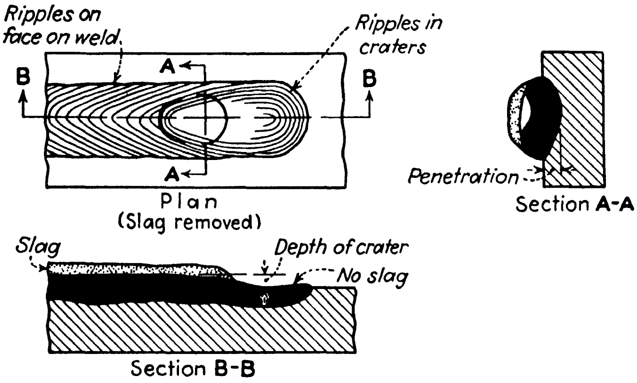
Arc Crater and Penetration.—At the point where the arc strikes the plate, if the current, polarity and speed of travel are correct, the metal is melted and forms a pool of molten metal. This molten metal seems to be forced out of the pool by some sort of blast from the arc. A small depression is thus formed in the base metal, and the molten metal is piled up around the edge of the depression which is referred to as the *arc crater* (see Fig. 156).

The size and depth of craters are dependent upon temperature, oxidation, surface tension, and other factors affecting fusion.

Weld craters are due to the pressure of the expanding gases and of the electron stream from the electrode tip and to the higher temperature at the center of the crater. The pressure of the expanding gases and of the electron stream blows the liquid metal toward the edges of the crater, and the higher temperature at the center of the crater results in a lower surface tension at that point, in comparison with the lower temperature and higher surface tension at the sides of the crater and adjacent metal. The equilibrium of the crater metal is upset by this difference in surface tension, and concentric waves result which freeze on reaching the colder edges or rim. This phenomenon can easily be noted during welding, and all completed welds have rippled faces. The angularity of the electrode



(a)- BARE ELECTRODE DEPOSIT
(One layer on plate surface)



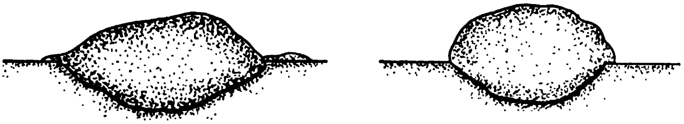
(b)-COVERED ELECTRODE DEPOSIT
(One layer on plate surface)
Note: Two craters, one without slag
and one with slag covering

FIG. 157—Typical shieded and unshielded metal-arc craters.

and the speed of welding determine the contour of the ripples (see Fig. 157).

During welding, the depth of the crater provides a means of observing the "penetration," or the depth to which the arc extends in the original metal (see Fig. 158). The depth of penetration should be one-third to one-half the total thickness of bevel and not less than $\frac{1}{16}$ in. Since fusion of the original metal is one of the requirements of a good weld, the soundness of the weld may be predicted from the penetration. However, the depth of a crater in a completed weld is not a definite indication of the depth of fusion or penetration; for craters of properly shielded processes are relatively shallow, and the crater may have been intentionally filled when the arc was broken.

The lack of a crater during welding is definite evidence that more heat must be generated for the parent metal to melt sufficiently to receive in fusion the molten metal from the filler rod.



(a)-Covered electrode deposit (b)-Bare electrode deposit

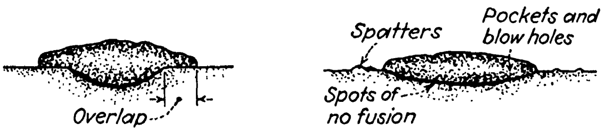
FIG. 158—Typical penetration obtained with coated (or covered) and bare electrodes. (One layer deposition.)

Arc Length and Arc Voltage.—There are three well-defined voltage zones in the welding arc: (1) cathode voltage drop; (2) anode voltage drop at the terminals; (3) the arc-stream voltage. The heat dissipated in each is in proportion to the voltage. The cathode and anode voltage drops remain practically constant and independent of the arc length and current. The arc-stream voltage varies with the arc length, but not in exact proportion thereto.

Good welds are not ensured by correct arc lengths only; but a long arc results in a poor weld, especially in welding with bare or lightly coated electrodes. The work is heated by the release of energy at the terminal of the arc, by the radiation and conduction from the arc core and stream, by the radiation from the hot surface of the electrode, and by the hot metal deposited upon it. If a short arc is used, the heat is concentrated upon the plate; with a long arc, a great deal of the heat is lost into the surrounding area. Thus, a short arc transforms a greater portion of the energy into useful heat.

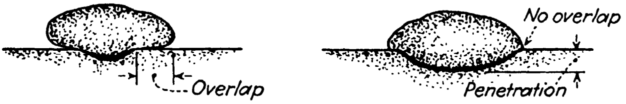
A long arc tends to wander over a considerable area on the work, and the arc flame blows about very rapidly; in other words, it is unstable. Because of this unstable condition of the arc and the greater length of the arc, the air has considerable opportunity to come in contact, not only with the metal passing from the electrode to the plate, but also with the very hot metal in the pool or crater. The hot metal thus absorbs oxygen and nitrogen, both of which are detrimental to the quality of the weld. With a short arc, the flame, consisting of vapors coming out of the arc, acts as a protection by surrounding the electrode metal and the arc pool, the absorption of these outside gases being thus largely prevented.

In shielded-arc welding, however, a longer arc may be used. As seen previously, the outside covering, burning more slowly than the electrode core, forms a protecting sheath and thus tends to prevent unstable conditions of the arc, as well as oxidation. The deposited weld metal is also protected from the atmosphere and from subsequent oxidation by a certain amount of slag that is formed on top of it.



(a)-Welding arc has traveled along too slowly

(b)-Too long arc used or too rapid travel



(c)- Not enough heat used

(d)-Weld which is satisfactory

FIG. 159.—Cross section of beads deposited under different conditions.

A long arc, besides causing welds of low strength, poor ductility, and high porosity, also prevents concentration of the deposit and causes excessive overlap, splattering and waste of material.

The kind and diameter of electrode and the current used determine the correct length of the arc. In bare-electrode welding the arc length should generally be approximately the same as the diameter of the electrode. Longer arcs are required by larger electrodes and higher currents.

Vertical, horizontal, and overhead welding require a shorter arc than flat welding. In the flat position, the normal arc voltage is 15 to 25 volts for $\frac{1}{8}$ to $\frac{1}{4}$-in. bare and lightly coated electrodes and 22 to 45 volts for coated electrodes. The voltages for the other welding positions are 2 to 5 volts less. With bare or lightly coated electrodes, a 15-volt arc is about $\frac{1}{8}$ in. long; with coated electrodes, a 40-volt arc is approximately $\frac{1}{4}$ in. long. For carbon-arc welding, the length of the arc is greater than for metallic-arc welding, usually ranging from $\frac{3}{8}$ to $\frac{7}{8}$ in., according to the current used. With a stable and proper carbon arc, a slight hissing sound is given off.

Welding Current Values.—The amount of current to be used depends upon many variables, and it is almost impossible to tabulate exact values. Practice and experience will teach the welding operator the proper values for various welding jobs.

The approximate or suggested values for the welding of ordinary low-carbon steel, with bare steel electrodes, are given in Table III.

TABLE III.—CURRENT VALUES FOR BARE ELECTRODES

Plate thickness, in.	Diameter of bare electrode, in.	Maximum arc length, in.	Approximate arc voltage, volts	Current range, amp.
1/16	3/32	3/32	14–16	40– 75
1/8	1/8	1/8	16–18	90–110
3/16	5/32	5/32	18–20	115–145
1/4	3/16	3/16	18–22	135–170
3/8	3/16	3/16	18–22	150–190
1/2	1/4	1/4	18–24	160–215
5/8	1/4	1/4	18–24	170–220
3/4	1/4	1/4	18–24	180–225
7/8	1/4	1/4	18–24	185–240
1	1/4	1/4	18–24	190–250

For shielded-arc welding, higher currents are used. Also, the current usually varies with each brand of shielded-arc electrode. Manufacturers of electrodes make recommendations which should, in general, be followed.

The recommended average current values for gas-producing electrodes are given in Table IV.

TABLE IV.—CURRENT VALUES FOR GAS-PRODUCING ELECTRODES

Electrode diameter, in.	Flat position, amp.	Vertical and overhead position, amp.
3/32	50–80	50–80
1/8	90–135	90–120
5/32	120–175	120–160
3/16	140–200	140–185
1/4	225–275	
5/16	300–375	
3/8	400–500	

The recommended average current values for heavy slag-producing electrodes are shown in Table V.

The tables show average values, and it must be kept in mind that these values differ under different conditions. There have been extreme cases when 300 amp. were used with a 3/16-in. electrode and 900 amp. with a 3/8-in. electrode.

TABLE V.—CURRENT VALUES FOR HEAVY SLAG-PRODUCING ELECTRODES

Electrode Diameter, In.	Flat Position, Amp.
1/8	130–150
5/32	160–180
3/16	200–260
1/4	300–400
5/16	400–600
3/8	500–900

Some of the factors determining the amount of current are: kind of material used, size and shape of work, type of joint, position of weld, skill of operator, equipment available, type of electrode, speed required, and so on.

Usually, materials considered as good conductors require more welding heat than poor conductors, for they absorb heat more rapidly. For the same reason, those parts which are larger require more current. Some joints, such as the lap and tee type, require somewhat higher currents for the first layer than other types, such as the butt, for the heat is conducted away more rapidly when they are used. Flat welding requires more current than vertical or overhead welding. At the beginning of a welding job, when the parts are cold, the current should be higher. As the parts become heated, the current may be reduced somewhat. Some operators prefer using a slightly larger electrode to reducing the current. In order to avoid excessive heating of the work and undue loss of alloying elements by volatilization or oxidation, electrodes with highly alloyed steel core should be used with currents slightly less than those required by common steel electrodes. Nonferrous electrodes need special consideration owing to their different melting point, heat conduction, coefficients of expansion, and other characteristics. No brief instruction for the successful han-

TABLE VI.—CURRENT VALUES FOR CARBON ELECTRODES

Diameter of carbon electrode, in.	Current used, amp.	Length of arc, in.
3/16	75	3/8
1/4	100	3/8
3/8	200	7/16
1/2	300	1/2
5/8	300	1/2
3/4	400	5/8
7/8	500	3/4
1	700	7/8

dling of these special electrodes can be given. Also, it must be kept in mind that the amount of current to be used may be limited by the available source of current. Ultimately, the greater the speed of welding, the greater the amount of current.

In carbon-arc welding, the amount of current to be used depends on the type of work; but the higher the current, the more stable the arc. On the other hand, the lower the current, the longer the electrode will last and the less the electrode holder will heat up.

Some average current values for carbon-arc welding are given in Table VI.

Stability of Arc.—For best welding results, it is necessary to have a stable arc, and the arc should remain uniform and steady. With an unstable arc, sound welds cannot be produced because of the likelihood of intermittent fusion, the trapping of the slag, and the production of blowholes. The character of the circuit supplying the current, the nature of the electrode, and the proper manipulation by the operator are the principal factors that influence stability.

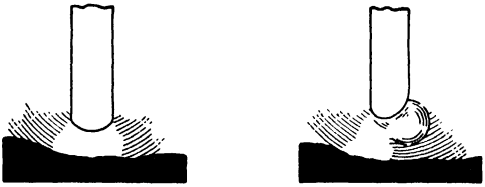

(a)-Stable metal arc (b)-Unstable metal arc

FIG. 160.—Stable and unstable metal arcs.

The arrangement of the source of current should be such that when the arc starts to go out, owing to lengthening, the voltage automatically rises instantly. This can be accomplished if the equipment is correctly designed. Also, because of lack of magnetic disturbances, alternating current gives a much more stable arc than direct current.

To promote arc stability, the electrode should be made of proper material and should have uniform consistency. The coatings on covered electrodes, besides protecting the arc, also assist in maintaining stability.

The chemical composition of the filler metal plays an important role in arc stability, besides affecting the physical properties of the weld metal. Coated electrodes greatly improve arc stability. The arc is extremely sensitive to the condition of the electrode surface. To illustrate, it has been found that an argon shielded arc will be erratic unless the electrode has at least a dust coating, which is a light coating of iron oxide obtained by a process of rusting after pickling wire in sulphuric acid. Arc stability is greatly affected by the presence in the electrode wire or on the electrode surface of certain substances in the form either of pure elements or of their oxides. Some of the materials that tend to stabilize the arc are iron oxide, calcium oxide, calcium carbonate, manganese oxide, and ferrous sulphide. Some of those which decrease stability are aluminum oxide, aluminum, silicon oxide, silicon, and ferrous sulphate.

Although of lesser importance the wire core should be of normalized grain structure, for the specific electric resistance of mild steel in this condition is most suitable for the purpose of arc welding. Also responsible for the erratic behavior of some coated electrodes is the lack of uniformity of the final heat-treatment of the wire core.

To overcome the "wild," or unsteady, arc often encountered in welding with bare electrodes, the electrodes may also be dipped in limewater. When the lime dries, some of it sticks to the wire and aids in steadying the arc.

An arc may be made unstable and may even be caused to go out by any steam or vapor that may form and arise in the arc.

Arc Blow.—Sometimes the arc has a tendency to waver from its intended path, especially in welding with bare steel electrodes on direct current. This phenomenon is known as "arc blow" and is generally considered to be caused by a magnetic disturbance in the neighborhood of the arc. Sometimes this disturbance is so great that the operator has great difficulty in making the weld; and it may be responsible for lack of fusion, porosity, and unevenly welded joints. At the same time, there is a considerable amount of splattering.

It is not always possible to determine the best way of eliminating this condition and to make the arc perform properly. However, the arc blow may generally be counteracted either by changing the position of the ground in relation to the work and welding away from the ground or by changing the position of the electrode in relation to the work. It may also be helpful to rearrange the parts to give a better mass distribution. For instance, backing strips should be used, a generous use of tack welds should be made, continuous root welds should be quickly deposited, or "starting" and "finishing" strips on the ends of the seams should be employed. A superimposed longitudinal magnetic field will also aid to prevent the blow.

A more detailed discussion of the magnetic condition existing about the arc will perhaps aid in understanding more clearly the undesirable phenomenon of arc blow.

When an electric current traverses a conductor, there is set up a magnetic field in a certain direction around the conductor. This magnetic field tends to travel in the path of least resistance and resists deflection from its intended path.

An illustrative condition is shown in Fig. 161. The weld extends from end 1 to end 4, with the ground connection being made to the backing bar at end 1. As the weld progresses from 1 to 4, the arc and arc flame will be found to show a decidedly forward pull for about one-eighth to one-quarter of the length of the seam. This pull is maximum at the start and becomes almost zero at 2. Between 2 and 3 the arc is most stable. At 3 the arc shows a backward pull which increases as welding proceeds to 4. This tendency to pull back may be enough to extinguish the arc. An extremely unstable arc therefore results.

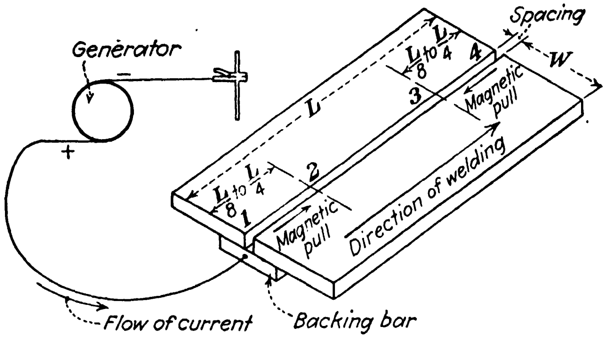


Fig. 161.—Magnetic pulls.

The magnetic field is set up in the plane of the parts being joined and circumferentially around the electrode and the plates, as shown in Fig. 162. Field F_1, is set up around the electrode; field F_2, around the plates being joined: and field F_3 in the plates adjacent to the arc and in a direction similar to that of field F_1. Of the three fields, field F_3 is the one that apparently causes the arc to draw away from either end of the weld. Since it is not possible to remove these fields from the welding operation, it is therefore necessary to use external control as a means to overcome these magnetic effects. As mentioned before, if the conditions allow, a magnetic field of proper direction and intensity may be imposed upon the work to cause the arc to become least affected by magnetic fields F_1 and

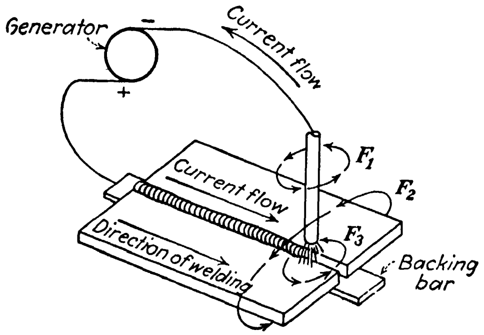
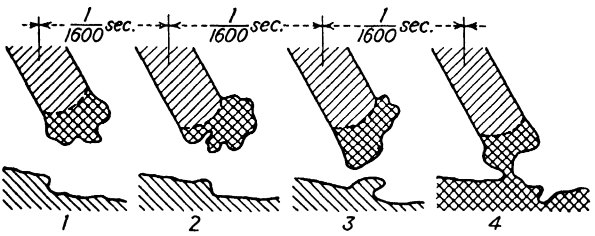


Fig. 162—Planes in which magnetic fields are set up.

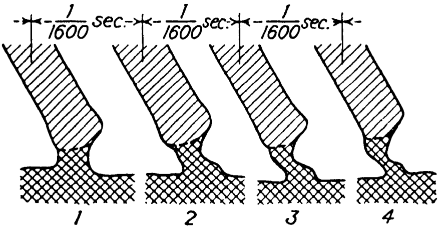
F_3. Field F_2 tends to cause the arc to draw slightly ahead, which is a desirable action, and therefore it is not harmful.

Arc blow does not exist in a.c. welding, and it is not quite so noticeable even with direct current provided that heavily coated electrodes are used.

Test of a Good Arc.—An experienced operator has no trouble in recognizing a good arc, being guided by both the appearance and the sound of the arc. As stated before, a long arc is unstable and causes small explosions which scatter larger globules of metal, whereas the short arc is surrounded by the protecting arc flame and ejects a steady shower of fine sparks. Also, a short arc makes a sharp rapid crackling sound resembling the sound of grease frying in a pan; a long arc hisses and is characterized by explosions occurring at steady intervals.



(a)-Globule or mushroom shaped transfer



(b)-Thread shaped transfer

FIG. 163.—Weld-metal deposition as observed in high-speed photographs of metallic-arc welding.

With a long arc the electrode is fused quite rapidly; but the directional control of the molten metal is poor, and some of the metal is not deposited where it is needed, splatter being the result. With a short arc, the electrode is not fused so rapidly, but more weld metal is deposited where it is useful.

Mechanism of Transfer of Metal.—The mechanism of transfer of metal is relatively simple in those shielded and unshielded processes in which the filler metal is independently fed into an uninterrupted arc stream that progressively melts both base metal or the previously deposited weld metal and the end of the filler metal in contact with the arc. With such processes, when the welding is done in a flat position, the molten globules of filler metal drop into the molten base metal by the force of gravity, whereas, in horizontal, vertical, and overhead welding, the molten globules are attracted to the molten base or weld metals into which they flow by surface tension.

In shielded and unshielded metallic-arc-welding processes, the transfer of the molten filler metal and molten slag is due to five separate and distinct forces or types of phenomena: (1) gravity; (2) gas expansion; (3) electromagnetic force; (4) electric forces; (5) surface tension.

Gravity is the major force playing a part in the transfer of filler metal and slag in flat welding. For welds made in this position, it facilitates a high deposition rate through the use of large electrodes. When welds are made in other positions, gravity compels the use of relatively smaller electrodes so as to avoid an excessive loss of weld metal and slag, for the surface tension is not capable of retaining a relatively large volume of molten metal and slag in the crater of the weld. To illustrate, a drop of water will remain suspended from the wet surface of a ceiling; but if another drop unites with it, a considerable amount of the combined drop will fall off.

Gas Expansion.—Under practical welding conditions, the high thermal energy absorbed in the arc not only liquefies and then gasifies all metallic and nonmetallic filler metal in the vicinity of the boiling electrode tip, but the rapid expansion of the gases projects the metallic and slag constituents of the electrode forward in globular form away from the solid electrode tip and into the molten crater previously formed in the base or weld metals. The gases involved in this action are those produced by the volatilization, combustion, and dissociation of the coatings or covering on the electrode, plus the carbon monoxide that is produced by the electrode wire. In welding with heavily coated electrodes, large volumes of gas are generated, and the sheath formed by the projecting covering at the electrode tip acts as a small but effective mortar for the directional projection of the globules. This action, due to the expansion of gases within the sheath, makes much easier the use of reverse-polarity d.c. and a.c. coated electrodes; it facilitates as well the making of welds in the horizontal, vertical, and overhead positions with these electrodes.

Electromagnetic Force.—When current is made to traverse a wire, there is created a magnetic force that acts at 90 deg. to the direction of current flow. Thus, the fluid globule in contact with the electrode tip acts as an electrical conductor and, as such, is subjected to this magnetic force. The magnetic force produces a pinching effect on the molten globule and speeds up the separation of the globule as the latter begins to neck down. This action undoubtedly aids the transfer of metal in welding in the horizontal, vertical, and overhead positions.

The *electric force*, due to the voltage differential in the arc, exerts a pull on the globule, pinched off by the electromagnetic force, in the same direction as the arc, regardless of the position in which welding is carried out. The use, in all positions, of d.c. straight-polarity electrodes, which do not produce large volume of gas, is greatly aided by the electric force.

Surface tension comes into play when filler metal and slag globules, with or without the aid of gravity, come close to, or in contact with, the molten base or weld metal in the crater. Surface tension not only attracts the liquid filler metal and slag globules into the liquid crater but ensures their appreciable retention in horizontal, vertical, and overhead welds. At the same time, it largely determines the shape of weld contours.

From the above discussion, the advantage and need of holding a close arc can be further seen. If welding with a long arc is done in a flat position, the globule of molten metal, which is formed at the end of the rod, grows until gravitation pulls it into the parent metal; but if a long arc is held in welding in an overhead position, the same force of gravitation causes the globule of metal to fall downward, possibly burning the hands of the operator.

Temperature of Welding Arc.—The temperature of the metallic arc is approximately 6500°F., whereas the temperature of the carbon arc has been found to vary from 6872 to 9572°F., depending upon the arc length and the graphite content of the electrodes. The atomic-hydrogen flame has a theoretical temperature of about 7254°F.; however, heat absorption due to the formation of atomic hydrogen reduces this to about 5342°F.

In general, the temperature of a welding arc is approximately the same as the boiling point of the electrode. It is affected by factors such as current surges, conduction, convection, and radiation.

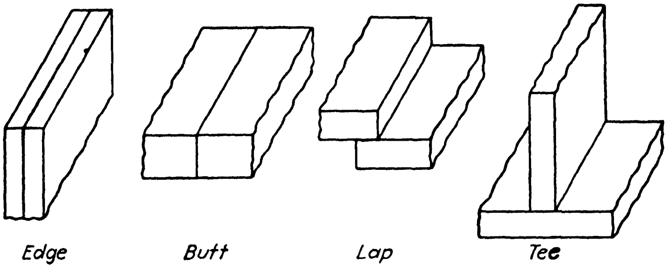
CHAPTER VIII

TECHNIQUE OF ARC WELDING *(Continued)*

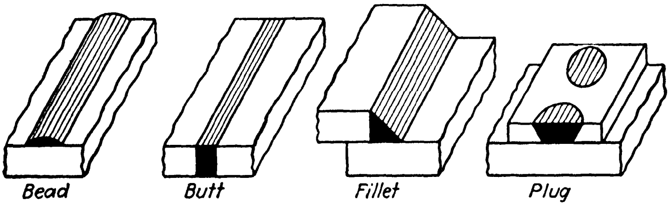
JOINTS, WELDS, AND STRESS DISTRIBUTION

Since the same forms of welds are very often used in the various forms of joints, it is essential clearly to differentiate between joints and their preparation and the welds joining the prepared parts.

The fundamental forms of joints are four: edge, butt, lap, and tee. The fundamental forms of welds, also four in number, are known as bead, butt, fillet, and plug (see Fig. 164).



(a)-Fundamental forms of joint



(b)-Fundamental forms of weld

FIG. 164.—Fundamental forms of joint and weld.

Many variations of the above fundamental forms have been introduced because of the requirements of design, cost, and practical welding. A description of most of these variations has been given in various parts of Chap. III and therefore will not be repeated here. However, a discussion of their proper selection for any given job follows.

Selection of Type of Joint.—A very important part of the arc-welding job is the selection of the best type of joint to be used in a particular application. The selection is sometimes dictated by the conditions, but very often a choice is possible.

Of course, the best joint is the least expensive one that will perform all the duties required. During the selection, three main factors must be considered: (1) the load and load characteristics, that is, whether the load is in compression or in tension, and whether bending, fatigue, or impact stresses in any combination are present; (2) the manner in which the load is applied, that is, whether load application is steady, variable, or sudden; (3) the cost of the joint preparation and the actual welding. Also to be considered are the effects of warping, the ease of welding, and the smoothness in appearance of the joint.

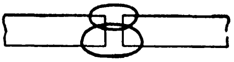


FIG. 165.—Plain butt joint.

The *plain butt joint* (Fig. 165), satisfactory for all usual loads, requires full and complete fusion, especially when the load is of a fatigue or an intermittent nature. Since a large portion of the base metal is melted during welding, the joint is generally used for thicknesses of ⅜ in. or less when welded with metallic electrode and for thicknesses of ¾ in. or lighter when carbon electrode is employed. The preparation of the joint for welding is very simple; it requires only a matching of the edges of the plate, separated by a distance that depends upon the plate thickness. Mainly because of the simple preparation required, the plain butt joint is low in cost.

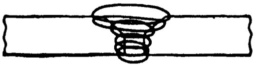


FIG. 166.—Single-Vee butt joint.

The *single-Vee butt joint* (Fig. 166) is suitable for all load conditions and is generally used with plate thicknesses considerably greater than the plain butt joint is, that is, ⅜ in. or heavier, but its use on thinner plate is not unusual. Preparation for this type of joint is more costly than for the plain butt joint. At the same time, more electrode is used in welding.

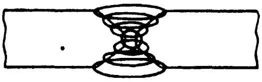


FIG. 167.—Double-Vee butt joint.

The *double-Vee butt joint* (Fig. 167) is satisfactory for all usual load conditions. It is used for plates of greater thicknesses than the single-Vee is and, of course, for work that can be welded from both sides. The double-Vee requires approximately half as much electrode as the single-Vee butt joint, but the cost of preparation for welding is higher.

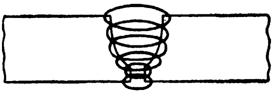


FIG. 168.—Single-U butt joint.

The *single-U butt joint* (Fig. 168) is used for work of the highest quality and is suitable for all usual load conditions. It replaces the single- or double-Vee butt joint for joining plates ½ to ¾ in. thick and is occasionally used on heavier plates. The single-U joint requires less weld metal than the single- or double-Vee, but the cost of machining the edges is greater. The welding is usually done on one side except for a single bead which is put in last on the opposite side from the U.

The *double-U butt joint* (Fig. 169) is satisfactory for all load conditions; and, if the welding can be done from both sides, it is used for the joining of heavy plates, ¾ in. and thicker. Less weld metal is required with this joint than with the single-U, but the cost of machining is greater.

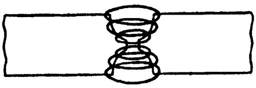


Fig. 169.—Double-U butt joint.

The *plain tee joint* (Fig. 170) is like the plain butt joint in that no machining of the plates is required. It is used for all ordinary plate thicknesses and mainly for loads that place the weld in longitudinal shear. Whenever severe impact or heavy transverse loads are applied, the non-uniform stress distribution of the joint should be kept in mind, and the stress intensity of the application should be duly taken into consideration. Of all the types of tee joints, the plain tee requires the most weld metal and has the highest electrode cost.

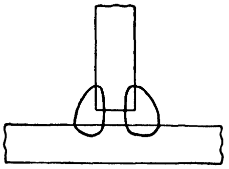


Fig. 170. Plain tee joint.

The *single-Vee tee joint* (Fig. 171) is able to withstand more severe loads than the plain tee, for it has better distribution of stress. In most cases, it is used for welding plates ½ in. in thickness or less, in work that can be welded from one side only. Though it is lower in electrode costs than the plain tee, the cost of machining is higher.

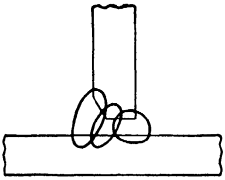


Fig. 171.—Single-Vee tee joint.

The *double-Vee tee joint* (Fig. 172) is used in joining heavy plates where the work can be welded from both sides and is suitable for heavy loads in longitudinal or transverse shear. The machining cost of the double-Vee is greater than for the single-Vee, but the electrode cost is less than for some other types such as a plain tee.

The *single-J tee joint* (Fig. 173) is able to withstand severe loads and is generally used for 1-in. plates or heavier, but it may also be applied to usual sized plates. Although the welding is done from one side only, it is advisable to put in a final finish bead on the side opposite the J. The single-J is somewhat more costly to machine than the single-Vee, but it is lower in electrode cost.

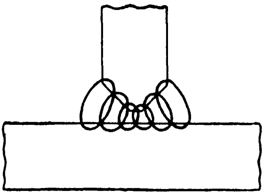


Fig. 172.—Double-Vee tee joint.

The *double-J tee joint* (Fig. 174) will withstand exceedingly severe loads of all types in heavy plates, 1½ in. or heavier, where welding can be done from both sides. The cost of machining for the double-J tee is higher than for other types of joints, but less electrode is required.

The *single-fillet lap joint* (Fig. 175) is very frequently used, for it requires practically no machining to fit the edges of the plate. If loading is not too severe, the single-fillet lap joint is suitable for welding plates of all thicknesses; but if fatigue or impact loads are encountered, stress distribution should be carefully studied.

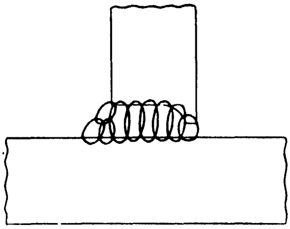


Fig. 173.—Single-J tee joint

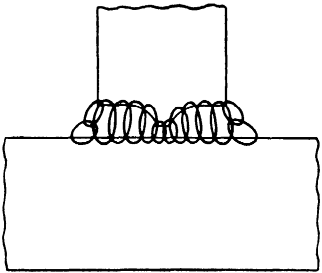


Fig. 174.—Double-J tee joint.

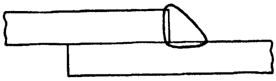


Fig. 175.—Single-fillet lap joint.

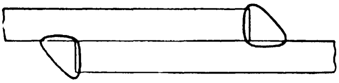


Fig. 176.—Double-fillet lap joint.

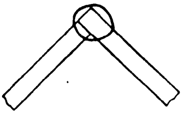


Fig. 177.—Flush corner joint.

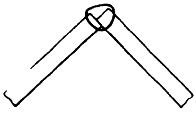


Fig. 178.—Half-open corner joint.

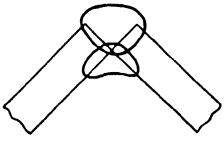


Fig. 179.—Full-open corner joint.

The *double-fillet lap joint* (Fig. 176) is suitable for much more severe load conditions than can be met by the single-fillet lap joint. As a rule both fillets should be full size, but in some cases one fillet may be smaller than the other. The double-fillet lap joint is chiefly used because its cost is lower; but, for extremely severe loads, the butt joint should be used.

The *flush corner joint* (Fig. 177) is suitable for welding plate, 12 gauge and lighter, where the loads are not severe. If used on heavier plates, care should be taken that loading is not excessive.

The *half-open corner joint* (Fig. 178) is generally used on plates heavier than 12 gauge where fatigue or impact is not severe. The tendency to burn through the plates at the corner is reduced by the "shouldering" effect of this type of joint.

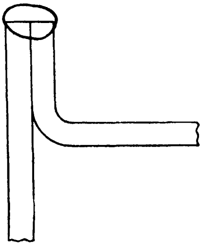


Fig. 180.—Edge joint.

The *full-open corner joint* (Fig. 179) is suitable for severe loads in welding plates of all thicknesses where the welding can be done from both sides. If properly made, it is of such shape that it provides good stress distribution; thus its application to fatigue or impact loads of all types is possible.

The *edge joint* (Fig. 180) is not suitable for severe loads, and careful consideration must be given to the load conditions, especially impact and fatigue. This type of joint is used for forming plates $\frac{1}{4}$ in. or less for light loads.

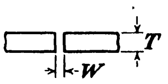
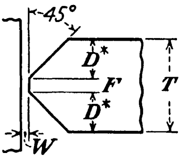
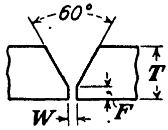
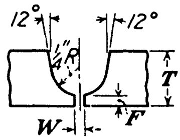
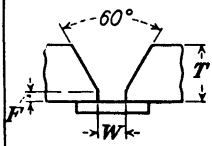
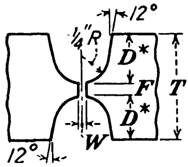
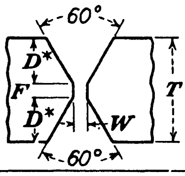
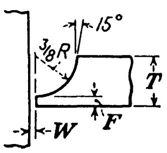
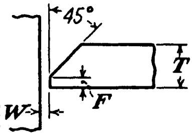
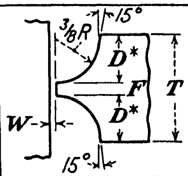
SHAPE OF GROOVE	T	W**	F	SHAPE OF GROOVE	T	W**	F
	$\frac{1}{8}$ to $\frac{3}{16}$	0 to $\frac{1}{16}$			$\frac{1}{2}$ & up	0 to $\frac{3}{16}$	0 to $\frac{1}{16}$
	$\frac{1}{4}$ & up	0 to $\frac{3}{16}$	0 to $\frac{1}{16}$		$\frac{3}{8}$ & up	0 to $\frac{1}{16}$	$\frac{1}{8} \pm \frac{1}{32}$
	$\frac{1}{4}$ & up	$\frac{3}{16}$ to $\frac{1}{4}$	0 to $\frac{1}{16}$		$\frac{3}{4}$ & up	0 to $\frac{1}{16}$	$\frac{1}{8} \pm \frac{1}{32}$
	$\frac{1}{2}$ & up	0 to $\frac{3}{16}$	0 to $\frac{1}{16}$		$\frac{3}{8}$ & up	0 to $\frac{1}{16}$	$\frac{1}{8} \pm \frac{1}{32}$
	$\frac{1}{4}$ & up	$\frac{1}{8}$ to $\frac{3}{16}$	0 to $\frac{1}{16}$		$\frac{3}{4}$ & up	0 to $\frac{1}{16}$	$\frac{1}{8} \pm \frac{1}{32}$

FIG. 181.—Typical proportions of metallic-arc weld grooves. *D. Usually equal, but may be any proportion desired. **The root opening desired in all butt welds, except U and J, should always be specified. Root opening of U and J welds is 0 in. unless otherwise specified.

In comparing the different forms of joints still further, it may be said that the butt joint is preferable to the single- and double-fillet lap joint (1) when the joint undergoes appreciable tension, bending, and fatigue stresses; (2) when overlapping parts would decrease thermal conductivity; (3) when overlapping surfaces would serve as conductors for liquids and gases, it being thus difficult to obtain tight structures; (4) when there is the possibility of corrosion between the overlapping surfaces; and (5) when a maximum saving in weight is desired.

Among the main disadvantages of the butt joint as compared with the lap joint are: (1) the greater cost of preparing the joint edges when beveled or grooved; (2) its higher assembly cost in the fabrication of some products; (3) the lack of design flexibility in weld size, for welds must of necessity be specified as having throat depths that are equal to or greater than the thickness of the thinner part joined; (4) the greater skill required to make the butt weld instead of the fillet weld; (5) the necessity of using smaller electrodes and lower currents for the root layers; (6) greater shrinkage; (7) higher residual stresses.

Similar advantages and disadvantages are present in edge and tee joints with their numerous combinations of fillet, butt, and bead welds.

Open and Closed Roots.—*Open roots* are used to ensure complete root penetration in square bevel and Vee butt welds and to secure attachment to a backing member. On the other hand, they may involve weld-metal penetration beyond the root face, irregular root fusion, and appreciable root movement of the parts formed. At times, these disadvantages are so great that single- and double-U butt welds with *closed roots* are used, even though the preparation of the grooves, which are usually machined, increases fabrication costs. If properly designed, these grooves facilitate complete root penetration without the projection of weld metal behind the root face. Since the movement of the parts being welded, due to weld shrinkage, is reduced to a minimum by the abutting root faces of the weld, the dimensions of the completed welded structure are also under better control.

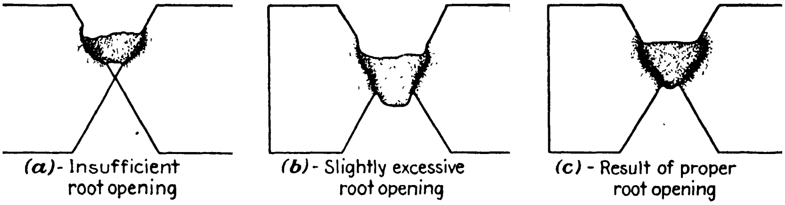

(a)- Insufficient root opening
(b)- Slightly excessive root opening
(c) - Result of proper root opening

FIG. 182.—Effect of root opening on Vee-grooved welds.

The resistance of the root faces of the weld to the movement of the parts joined by single- or double-U welds results in higher residual stresses, but these can be controlled by some means of stress relieving (see Chap. XI).

Intermittent Welds.—A weld of broken continuity is known as an *intermittent weld*. Usually, these welds consist of comparatively short beads spaced on equidistant centers, so that uniform strength is had for full length of the seam.

Tack Welds.—A *tack weld* is a weld used to hold parts together, for assembly purposes only, prior to complete welding. It should be made by a process that is approved for the class of welding called for on the work.

Craters in all tack welds should be properly filled at the time they are made in order to prevent the starting of cracks at this point.

The thickness of the plates, length of seam, and general nature of the job determine the frequency and length of tack welds. As a rule, a tack weld is made approximately twice as long as the thickness of the plate being tacked.

Calking Welds.—When the strength of the joint is ensured by other methods and a weld is added merely to secure a joint that will not leak under prescribed pressure tests with air, oil, or water, it is called a *calking weld.*

Composite Welds.—A *composite weld* is one that must meet certain requirements of both strength and tightness.

Position of Welds.—There are four fundamental positions of welds. They are designated as flat, vertical, horizontal, and overhead (see Fig. 28, Chap. III).

A *flat weld* is a weld made in a horizontal plane or in a plane inclined at an angle of 30 deg. or less to the horizontal, with the welding end of the electrode pointing generally downward from above.

A *vertical weld* is one made in a vertical plane or in a plane inclined 60 deg. or less to the vertical, with the line of weld running vertically.

A *horizontal weld* is one made in a vertical plane or in a plane nearly vertical, with the line of weld running horizontally. The direction of the line of weld is the only difference between a vertical weld and a horizontal weld.

An *overhead weld* is a weld made on the underside of a horizontal plane or in a plane inclined so that the welding end of the electrode must point upward from below. Overhead welds are just the opposite of flat welds.

Since welding in the flat position is generally speedier and less fatiguing than welding in other positions, wherever it is practical to do so the work should be so located that only flat welds are necessary. However, in many instances, the bulk of the parts or the character of the work requires that some of the welds be made in the other positions.

Dimension of Welds.—The size of a butt weld is measured by its net, or unreinforced, throat dimension. In general, a butt weld is the same size as the thickness of the plates it joins. The size of a fillet weld is the length of a leg of the weld (see Fig. 183; also Size of Weld, Chap. III).

Reinforcement of Welds.—Provided that the physical properties of the weld metal are equal or superior to those of the base metal, properly made butt welds should not be reinforced beyond the minimum required to ensure the required depth of throat (see Fig. 67, Chap. III). The throat depth should be increased from 10 to 20 per cent in cases where there is a question of the possible quality of weld metal, residual stresses, or workmanship. When the full-open corner welds, also known as "corner butt welds," are used in stressed products, both the face and the root should be reinforced, for the shape of the section tends to localize bending and other stresses in the weld. Experience has shown that, even in unstressed products, failures of fillet and full-open corner welds are a common occurrence because of inadequate throat depths or because of the sloughing away of the base metal (Fig. 184*B*).

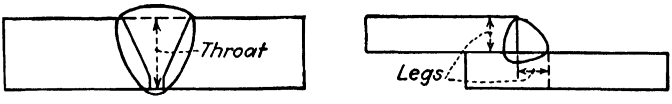


FIG. 183.—Where size of weld is measured.

Strength of Welds.—With few exceptions, welded joints can be made as strong as the parts to be joined. However, all welds should be designed with the minimum amount of weld metal that is adequate for the needs of the job. Deposited weld metal may run from 50 cents to $1 per pound, whereas the steel on which the weld metal is deposited may cost from 2 to 6 cents per pound. Thus, the value of proper welds can readily be understood.

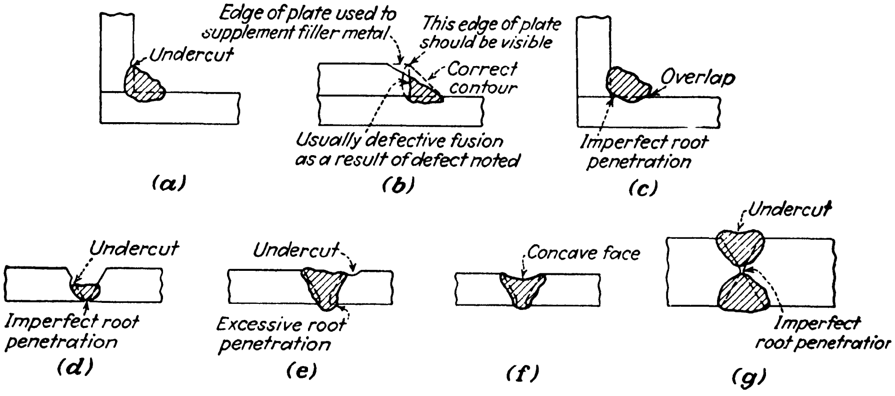

Edge of plate used to supplement filler metal
This edge of plate should be visible
Undercut
Correct contour
Overlap
Usually defective fusion as a result of defect noted
Imperfect root penetration
(a)
(b)
(c)
Undercut
Undercut
Undercut
Concave face
Imperfect root penetration
Excessive root penetration
Imperfect root penetration
(d)
(e)
(f)
(g)

FIG. 184.—Typical root, toe, and face of fillet and butt welds.

Some of the variables that influence the strength of a welded joint are: strength of the deposited weld metal, type of joint and weld, size of the weld, location of the weld in relation to the parts joined, kind of stresses to which the joint will be subjected in use, conditions under which the welding is done, type of equipment used for welding, skill of the welding operator, and so on. The size, type, and location of every weld is particularly important where weld failure might endanger life or limb.

Ultimate Strengths.—Weld metal deposited with mild-steel bare or lightly coated electrodes has an ultimate tensile strength ranging from 40,000 to 55,000 lb. per sq. in. The Code for Fusion Welding (structural) allows an average tensile strength of 45,000 lb. per sq. in. Welds made by the shielded-arc process have an ultimate tensile strength of 60,000 to 75,000 lb. per sq. in. These values are to be compared with the ultimate tensile strength of rolled mild steel which ranges from 55,000 to 65,000 lb. per sq. in.

Working Strengths.—When the weld metal is deposited with mild-steel bare electrodes, the following values are used for static loads: working tensile strength, 13,000 lb. per sq. in.; working shearing strength, 11,300 lb. per sq. in.; working compression strength, 15,000 lb. per sq. in. However, with heavily coated electrodes, the shielded-arc process being used, values 20 to 30 per cent higher than the above can be used in safety.

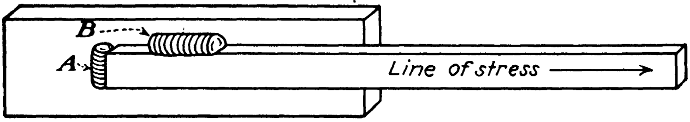


FIG. 185.—Location of welds in relation to line of stress.

The following table gives the safe working values for fillet welds in shear, as well as for butt welds in tension and compression.

TABLE VII.—SAFE ALLOWABLE STATIC LOADS FOR WELDS WITH BARE ELECTRODES*

Size of throat of butt weld or leg of fillet weld, in.	Butt weld in tension	Butt weld in compression	Fillet weld in shear
1/8	1,625	1,875	1,000
3/16	2,438	2,813	1,500
1/4	3,250	3,750	2,000
5/16	4,062	4,687	2,500
3/8	4,875	5,625	3,000
1/2	6,500	7,500	4,000
5/8	8,125	9,375	5,000
3/4	9,750	11,250	6,000

* Values given are in pounds per linear inch.

If dynamic, vibrational, or lifting loads are applied, the unit stress of fillet welds should be reduced, depending upon the severity of the load.

As mentioned in Chap. I, welded joints can easily be made stronger than riveted joints. The lengths of weld fillets corresponding in shearing strength to rivets of various sizes are given in Table VIII. To make up for any possible weak spots at the starting and stopping of the arc, the fillet should be made about ¼ in. longer than required.

In many cases, the strength of the welded joint is affected by the location of the welds in relation to the parts joined. Other factors being equal, welds having their linear dimensions transverse to the lines of stress are approximately 30 per cent stronger than welds with linear dimensions parallel to lines of stress (see Fig. 185).

Classification of Welds.—Metallic-arc welds are classified according to the tensile strength required and the material to be welded. A table showing the minimum physical properties of welds of the various classes, as specified by codes in force in the United States, is given in Table IX.

Stress Distribution.—In some designs, the distribution of stress through the welds in a joint must be taken into consideration. An abrupt change in surface, such as a notch or saw cut in a square bar under tension, increases the local stress or causes stress concentration. Figure 186 illustrates this principle. In Fig. 186*A* the stress concentration is much greater than that in Fig. 186*B*. A more uniform transfer of stress and a resultant minimum of stress concentration are shown in Fig. 186*C*. In heavy or repeated loadings, this matter should be carefully considered.

TABLE VIII.—LENGTH OF FILLET WELD TO REPLACE RIVETS

Rivet diameter size, in.	Rivet shear value, 12,000 lb. per sq. in.	Length of fillet welds (to nearest ⅛ in.)									
		¼-in. Bead		5/16-in. Bead		⅜-in. Bead		½-in. Bead		⅝-in. Bead	
		Shielded arc	"Fusion code"	Shielded arc	"Fusion code"	Shielded arc	"Fusion code"	Shielded arc	"Fusion code"	Shielded arc	"Fusion code"
½	2,356	1¼	1½	1	1¼	⅞	1	¾	⅞	⅝	¾
⅝	3,682	1¾	2⅛	1⅜	1¾	1¼	1½	1	1⅛	⅞	1
¾	5,301	2⅜	3	2	2⅜	1¾	2	1¼	1½	1⅛	1⅜
⅞	7,216	3⅛	3⅞	2½	3⅛	2⅛	2⅝	1¾	2	1⅜	1¾
1	9,425	4	5	3¼	4	2¾	3⅜	2⅛	2⅝	1¾	2⅛

NOTE: ¼ in. is added to calculated length of bead.

However, in many cases, such concentration of stress might be small or of minor consequence.

In welds that have their linear dimensions approximately parallel to the line of force, the stress is not evenly distributed. Depending on the load conditions, the stress is often greater at the ends of the weld than in the middle. In certain conditions, to obtain far greater resistance to a tearing action on the weld, it is advisable to hook the bead around the joint as shown in Fig. 187.

TABLE IX.—MINIMUM PHYSICAL PROPERTIES OF WELDS

Class of welding			1	2	3
Material			Low-carbon steel, B4A12C or equivalent*	Low-carbon steel, B4A8 or equivalent†	Low-carbon steel, B4A8 or equivalent‡
Joint	Tensile strength, lb. per sq. in.		55,000	52,000	45,000
	Yield point, lb. per sq. in.		40,000	40,000	35,000
	Free bend, per cent elongation		30%	20%	10%
	Corrosion resistance relative to plate stock		100%	100%	50%
All weld metal	Tensile strength, lb. per sq. in.		60,000	60,000	50,000
	Yield point, lb. per sq. in.		45,000	45,000	40,000
	Elongation in 2 in.		20%	20%	10%
	Density		7.80	7.78	7.75
	Charpy impact, ft.-lb.		30	20	2
	Endurance limit, lb. per sq. in.		28,000	25,000	12,000
Fillet weld ultimate shear strength, lb. per lin. in.		Size, in.			
		¼	......	11,000	10,000
		⅜	14,000	14,000	13,000
		½	18,000	18,000	16,000
		⅝	21,000	21,000	19,000
		¾	25,000	25,000	21,000

NOTE: Above values are ultimate. Use a factor of safety. Values are for the "as-welded" or "stress-relieved" condition.

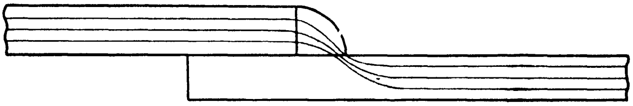
* A.S.M.E. Power Boiler Code, Par. P. 102; A.S.M.E. Code for Unfired Pressure Vessels, Par. U-68.

† A.S.A. Code for Pressure Piping, Par. 518; A.S.M.E. Code for Unfired Pressure Vessels, Par. U-69.

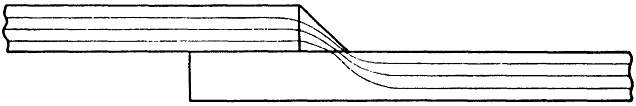
‡ A.W.S. Fusion Welding and Gas Cutting in Building Construction; A.S.M.E. Code for Unfired Pressure Vessels, Par. U-70.

Use of Polarized Light to Study Stress Distribution.—By employing polarized light and transparent models, a study of stress distribution in welded joints can be made easily and at not too great a cost. It is based upon the following principle: When polarized light is passed through a transparent substance, such as celluloid, it is broken into different colors or different shades of the same color, depending on the condition of stress present in the specimen and on the source of light supply.

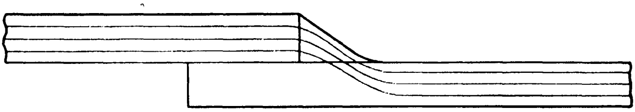
In this type of stress investigation, the celluloid model is cut in exact replica of the welded joint to be studied. The model is then inserted in the polariscope (see Fig. 188), and polarized light is passed through it onto a projection surface or screen. When stress is applied to the celluloid model, its distribution, intensity, and concentration will be shown, in the image projected, by the familiar colored band formation.



(a)-Example of lap weld having poor distribution of stress through weld



(b)-Example of lap weld having a more even distribution of stress through weld



(c)-Example of lap weld in which there is a fairly uniform transfer of stress through the weld

FIG. 186.—Stress distribution with differently shaped fillet welds.

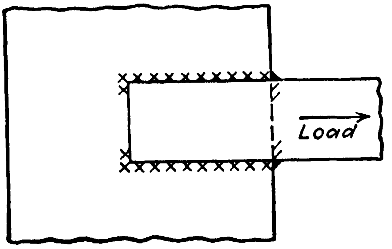


FIG. 187.—Example of welds hooked around the corners to obtain resistance to tearing action on welds.

When white polarized light is passed through celluloid that has not been stressed, a rather dark gray image is shown. If the celluloid is subjected to tension, a yellow color will be projected. A continued slow increase of the tension will change the yellow to orange, then to red, to violet, to blue, to green. With further stress, the projected color will change from green to yellow and through the various colors of the spectrum of white light in the order previously named. This cycle continues as the celluloid is stressed to the breaking point. If the tension is slowly released, the projected series of color will be reversed. For instance, if blue were the color when tension was released, the color would change to violet, to red, to orange, to yellow.

When a single-color light source is used, light and dark shades of the color will be projected (see Fig. 189).

This method of study of stress distribution in welded joints will also reveal that the shape of the joint or part has a marked effect upon the distribution of stress. For instance, it will be found that in a heavily reinforced single-Vee butt joint, a model of which is shown in Fig. 190*a*, the stress is localized at the edges of the bead and the top of the reinforcement carries practically no stress. The distribution of stress is materially changed and uniformity is greatly increased if the change in contour at the junction of weld with base metal is made less abrupt (Fig. 190*b*). A still more uniform distribution of stress is caused by further reduction of the reinforced portion of the joint, or, better yet, by the complete elimination of the reinforcement (Fig. 190c).

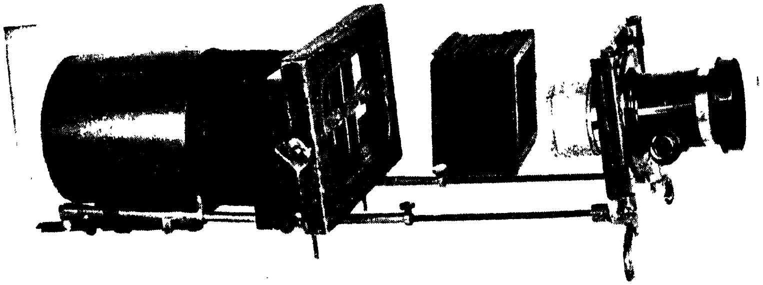
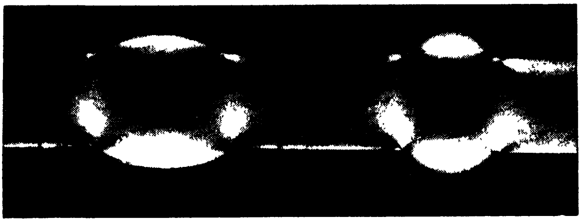


FIG. 188.—Slide projector modified to project models on screen. (*Courtesy of The Lincoln Electric Company.*)

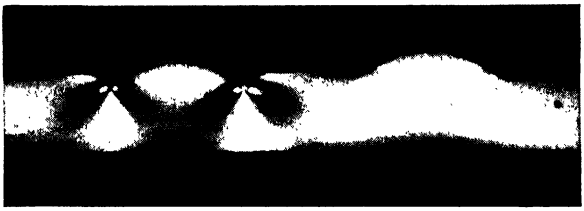
Improperly designed or improperly executed welded joints can be studied by the same means. The model shown in Fig. 190*d* represents a single-Vee butt having a void at the bottom of the Vee. When stressed and subjected to polarized light, the model will show that there is a decided concentration of stress at the nick, or unpenetrated portion of the joint (see Fig. 189*d*). The model (Fig. 190*e*) represents a butt joint with overlapping welds. When stressed in a polariscope, it will show stress concentration at the joint of weld metal at the surface of the base metal.

These studies of stress distribution clearly show that the additional weld metal used as reinforcement is not worked to any degree and is, therefore, practically useless. It is simply a superfluity of weld metal of no particular value. Thus, it may be said that the amount of reinforcement of a weld does not necessarily mean added strength of joint.

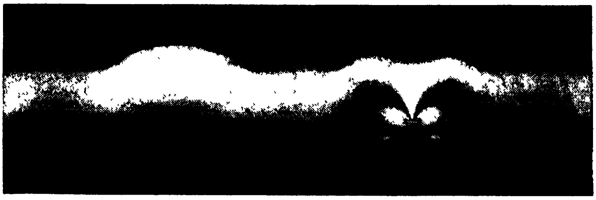
(*a*) Usual type of single-Vee and double-Vee butt joint.



(*b*) Comparison of the usual double-Vee butt weld with an abnormally reinforced double-Vee butt weld.



(*c*) Effect of undercutting.



(*d*) Usual type of single-Vee butt weld compared with single-Vee butt weld with lack of penetration.

FIG. 189.—Various types of welded joints under stress. (*Courtesy of The Lincoln Electric Company.*)

For lap joints, it could be shown that the reinforced portions of the lap or fillet welds are not worked when stress is applied to the joint. Also, in a lap weld having a gradual slope, stress is more uniformly distributed.

The point of stress concentration may be located by observation and different designs compared. Stress concentrations occur wherever there is a marked crowding together or abrupt curving of the bands.

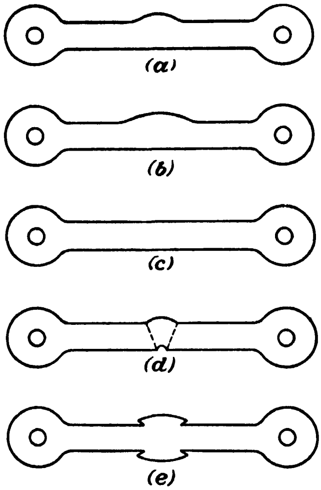


Fig. 190.—Models of welded joints.

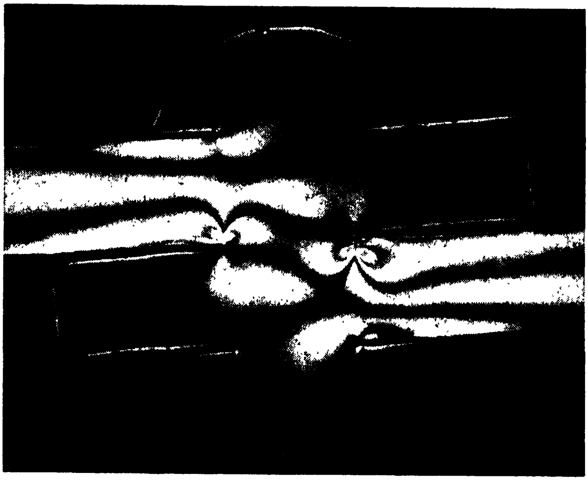


Fig. 191.—Single-rivet lap joint. (The quick change of direction and the crowding together of the lines at the intersection of the rivet and the base metal indicate very high stresses at these points.) (*Courtesy of The Lincoln Electric Company.*)

An analogy might be drawn between the distribution of stresses and the streamlined flow of water. The gradual changes in sections and the omissions of internal and external irregularities would ensure the uniformity of stress, as lack of turbulence and splash would secure a smooth flow of water.

CHAPTER IX

TECHNIQUE OF ARC WELDING (*Continued*)

LAYER SEQUENCES, DEPOSITION RATES, AND COSTS

It is usually essential progressively to deposit weld metal in a series of superimposed beads or layers not exceeding ⅛ in. of thickness in order to produce the highest quality welds. Thin layers are necessary for effective peening and to ensure that each layer normalizes the lower adjacent one throughout its entire depth, but it must be kept in mind that the extremely localized normalizing does not eliminate residual thermal stresses in the weld or structure as a whole. The methods by which these stresses can be eliminated or appreciably reduced are given in Chap. X.

Tabulation of Values.[1]—The values shown in the following tables, though correct, are only average figures and therefore should not be taken as being exact for every application. Rather, they may be depended upon only for general guidance.

Before applying any of the data in this section, a careful study of the specific application should be made, and the procedure should be changed according to the desired quality, fit-up, and rate of dissipation of heat into the members to be joined.

The values for welding speeds are actual welding time, without any allowance for fatigue, cleaning, setting up, and so on.

It must also be remembered that variations in current from those shown will affect the welding speed. Also, poor fit-up and other conditions will affect the amount of electrode deposited per foot of weld.

Estimating the Cost of Welds.—In estimating the cost of deposited weld metal, various factors must be taken into consideration. Among these are labor, power, electrodes, efficiency of welding machine, and overhead. The overhead charge will be omitted in this discussion because it varies widely among different plants. Only the direct costs will be included, but it must be kept in mind that they may also vary, depending upon local conditions.

To illustrate more fully how the cost of welds may be arrived at or estimated, a sample computation is given.

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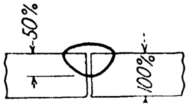
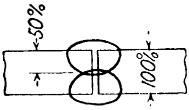
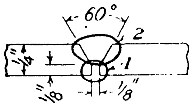
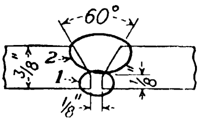
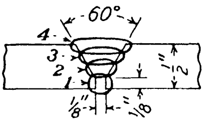
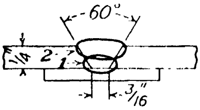
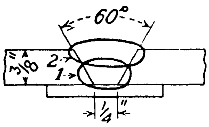
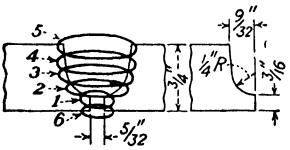
[1] Data in the tables have been supplied by The Lincoln Electric Co. and are published through their courtesy.

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES

Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	3/16 in.	Flat	1	1/4	190	30	90	0 078
	1/4 in.	Flat	1	5/16	300	34	90	0 133
	3/8 in	Flat	1	5/16	425	38	75	0 226
	1/2 in.	Flat	1	3/8	500	40	50	0 46
	3/16 in.	Flat	2	1/4	190	30	47	0 16
	1/4 in.	Flat	2	5/16	300	34	45	0 27
	3/8 in.	Flat	2	5/16	425	38	37½	0 45
	1/2 in.	Flat	2	3/8	500	40	25	0.92
	1/4 in.	Flat	1	5/32	130	25		0 11
			2*	3/16	175	28	17 5	0 25
								0 36
	3/8 in.	Flat	1	5/32	130	25		0 15
			2*	1/4	225	30	13	0 43
								0 58
	1/2 in.	Flat	1	5/32	130	25		0 16
			2	1/4	225	30		0 24
			3	1/4	275	30		0 26
			4*	5/16	325	38	9	0 35
								1.01
	1/4 in.	Flat	1	5/16	325	34		0 172
			2	3/8	425	38	33.5	0 325
								0 497
	3/8 in.	Flat	1	5/16	325	34		0.198
			2	3/8	425	38	27 5	0.44
								0.638
 5 4 3 2 1 6 5/32" 3/4" 1/4"R 9/32" 3/16"	3/4 in.	Flat	1	5/32	130	25		
			2	1/4	275	30		
			3	1/4	275	30		
			4	1/4	275	30		
			5	5/16	325	34		
			6	1/4	275	30	6	1.90

* Weaved bead.

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

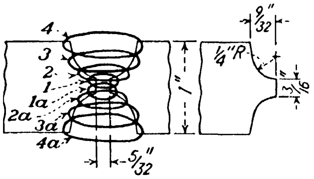
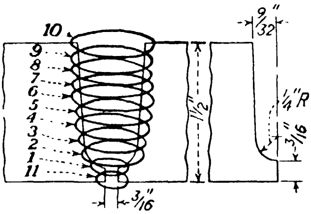
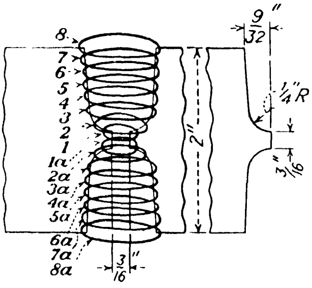
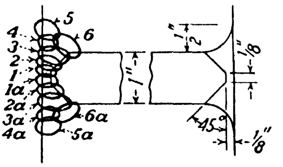
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
 4 3 2 1 1a 2a 3a 4a 9/32" 1/4"R 3/16" 1" 5/32"	1 in.	Flat	1	5/32	130	25		
			1a	1/4	275	30		
			2	1/4	275	30		
			2a	1/4	275	30		
			3	1/4	275	30		
			3a	1/4	275	30		
			4	5/16	325	34		
			4a	5/16	325	34	3.8	2.28
 10 9 8 7 6 5 4 3 2 1 11 9/32" 1/4"R 3/16" 1 1/2" 3/16"	1½ in.	Flat	1	5/32	130	25		
			2	1/4	275	30		
			3	1/4	275	30		
			4	1/4	275	30		
			5	1/4	275	30		
			6	1/4	275	30		
			7	1/4	275	30		
			8	1/4	275	30		
			9	1/4	275	30		
			10	5/16	325	34		
			11	5/16	325	34	2.5	3.70
 8 7 6 5 4 3 2 1 1a 2a 3a 4a 5a 6a 7a 8a 9/32" 1/4"R 3/16" 2" 3/16"	2 in.	Flat	1	5/32	130	25		
			1a	1/4	275	30		
			2	1/4	275	30		
			2a	1/4	275	30		
			3	1/4	275	30		
			3a	1/4	275	30		
			4	1/4	275	30		
			4a	1/4	275	30		
			5	1/4	275	30		
			5a	1/4	275	30		
			6	1/4	275	30		
			6a	1/4	275	30		
			7	1/4	275	30		
			7a	1/4	275	30		
			8	5/16	325	34		
			8a	5/16	325	34	1.80	4.35
 5 6 4 3 2 1 1a 2a 3a 4a 6a 5a 1/2" 1" 1/8" 45° 1/8"	1 in.	Flat	1-1a	5/32	130	25		
			2-2a	1/4	275	30		
			3-3a	5/16	325	34		
			4-4a 5-5a 6-6a	1/4	190	30	2.42	3.22

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

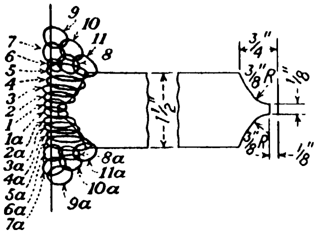
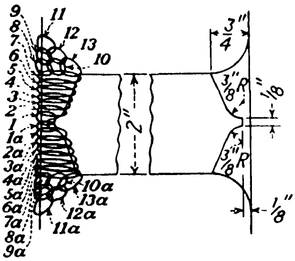
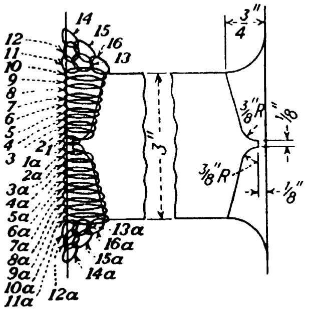
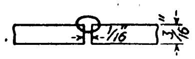
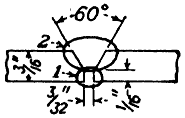
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
 9 10 11 8 7 6 5 4 3 2 1 1a 2a 3a 4a 5a 6a 7a 8a 11a 10a 9a 1½" 3/4" 3/8"R 1/8" 3/8"R 1/8"	1½ in.	Flat	1-1*a* 2-4*a* 5-5*a* 6-11*a*	5/32 1/4 5/16 1/4	130 275 325 190	25 30 34 30	1.00	7.04
 9 8 7 6 5 4 3 2 1 1a 2a 3a 4a 5a 6a 7a 8a 9a 11 12 13 10 10a 13a 12a 11a 2" 3/4" 3/8"R 1/8" 3/8"R 1/8"	2 in.	Flat	1-1*a* 2-6*a* 7-7*a* 8-13*a*	5/32 1/4 5/16 1/4	130 275 325 190	25 30 34 30	0 83	9 51
 14 15 16 13 12 11 10 9 8 7 6 5 4 21 3 1a 2a 3a 4a 5a 6a 7a 8a 9a 10a 11a 12a 13a 16a 15a 14a 3" 3/4" 3/8"R 1/8" 3/8"R 1/8"	3 in.	Flat	1-1*a* 2-9*a* 10-10*a* 11-16*a*	5/32 1/4 5/16 1/4	130 275 325 190	25 30 34 30	0 64	12.05
	3/16 in.	Vertical (Uphill)	1	1/8	110	25	20	0.15
	3/16 in.	Vertical (Downhill)	1 2	1/8 3/16	110 150	25 25	25	0.18

Table X.—Layer Sequences and Deposition Rates.—(*Continued*)

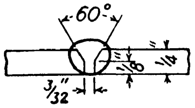
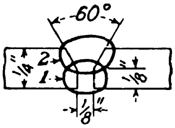
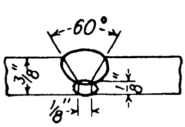
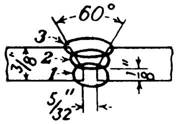
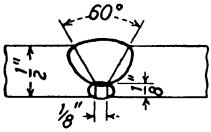
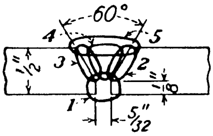
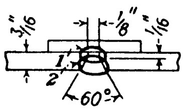
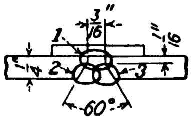
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	¼ in.	Vertical (Uphill)	1	⅛	110	25	15	0.24
	¼ in.	Vertical (Downhill)	1 2	⅛ 3/16	110 150	25 25	17.5	0.29
	⅜ in.	Vertical (Uphill)	1 2	5/32 5/32	130 130	25 25	9.75	0.44
	⅜ in.	Vertical (Downhill)	3	3/16	150	25	11	0.44
	½ in.	Vertical (Uphill)	1 2	5/32 5/32	130 130	25 25	5.25	0.72
	½ in.	Vertical (Downhill)	5	3/16	150	25	7	0.72
	3/16 in.	Overhead	1 2	⅛ 3/16	110 150	25 25	14	0.33
	¼ in.	Overhead	1 2 3	⅛ 3/16 3/16	110 150 150	25 25 25	9	0.45

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

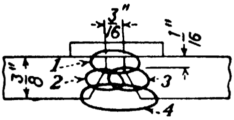
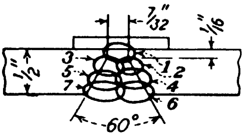
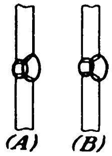
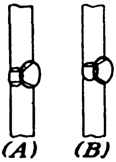
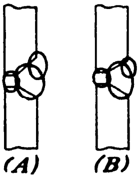
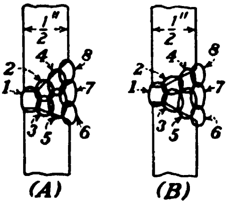
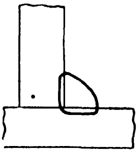
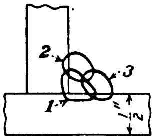
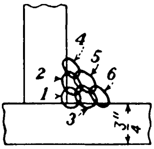
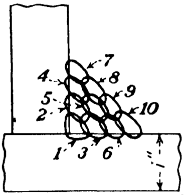
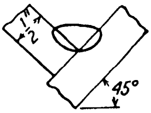
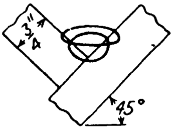
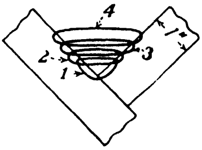
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	3/8 in.	Overhead	1 2 3 4	1/8 5/32 3/16 3/16	110 130 150 150	25 25 25 25	6	0.70
 7/32" 1/16" 1/2" 3 5 7 1 2 4 6 60°	1/2 in.	Overhead	1 2–3 4–7	1/8 5/32 3/16	110 130 150	25 25 25	4	1.15
 (A) (B)	3/16 in. 3/16 in.	Horizontal	2 2	5/32 5/32	130 130	25 25	24 25	0.16 0.15
 (A) (B)	1/4 in. 1/4 in.	Horizontal	2 2	5/32 5/32	130 130	25 25	17.5 18	0.23 0.22
 (A) (B)	3/8 in. 3/8 in.	Horizontal	3 3	5/32 5/32	130 130	25 25	10.5 11	0.38 0.37
 1/2" 2 1 4 8 7 3 5 6 (A) 1/2" 2 1 4 8 7 3 5 6 (B) (A) (B)	1/2 in. 1/2 in.	Horizontal	8 8	5/32 5/32	130 130	25 25	4.4 4.6	0.86 0.83

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	3/16 in. 1/4 in. 3/8 in.	Flat Flat Flat	1 1 1	1/4 1/4 1/4	190 190 190	30 30 30	45 35 20	0.155 0.20 0.37
	1/2 in.	Flat	3	1/4	190	30	10	0.70
	3/4 in.	Flat	6	1/4	190	30	4	1.83
	1 in.	Flat	10	1/4	190	30	2.25	3.25
	1/2 in.	Flat	1	3/8	350	36	26	0.63
	3/4 in.	Flat	1 2*	3/8 3/8	350 500	36 40	 13½	 1 46
	1 in.	Flat	1 2* 3* 4*	3/8 3/8 3/8 3/8	350 500 500 500	36 40 40 40	 8	 2.60

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* Weaved bead.

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

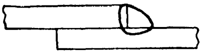
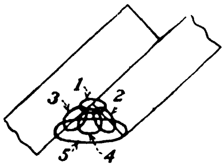
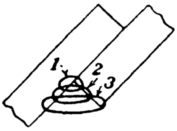
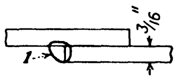
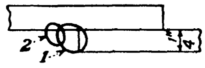
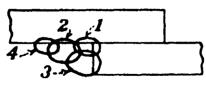
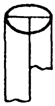
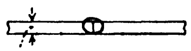
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed ft. per hr.	Lb. of electrodes per ft.
	⅛ in.	Flat	1	¼	250	30	100	0.097
	3/16 in.	Flat	1	¼	250	30	90	0.120
	¼ in.	Flat	1	¼	250	30	70	0.138
	5/16 in.	Flat	1	¼	250	30	50	0.19
	⅜ in.	Flat	1	¼	250	30	40	0.137
	3/16 in.	Vertical (Downhill)	1	3/16	150	25	35	0 12
	¼ in.	Vertical	2	3/16	150	25	19	0.25
	⅜ in.	Vertical	3	3/16	150	25	12	0.40
	½ in.	Vertical	5	3/16	150	25	6.5	0.72
	¾ in.	Vertical	9	3/16	150	25	3.25	1.5
	1 in.	Vertical	14	3/16	150	25	1.7	2 75
	3/16 in.	Vertical (Uphill)	1	⅛	110	25	18	0 16
	¼ in.	Vertical	1	5/32	130	25	18	0 23
	⅜ in.	Vertical	1	5/32	130	25	9.5	0 42
	½ in.	Vertical	2	5/32	130	25	5	0.72
	¾ in.	Vertical	3	3/16	150	25	3 25	1.45
	1 in.	Vertical	4	3/16	150	25	1.7	2 60
	3/16 in.	Overhead	1	3/16	150	25	35	0 120
	¼ in.	Overhead	1	3/16	150	25		
			2	⅛	110	25	15	0 26
	⅜ in.	Overhead	1-2-3	3/16	150	25		
			4	⅛	110	25	9½	0 53
	½ in.	Overhead	1-5	3/16	150	25	6½	0 75
	⅛ in.	Flat	1	¼	170	30	165	0 030
	3/16 in.	Flat	1	¼	225	30	140	0 062
	¼ in.	Flat	1	5/16	325	34	135	0 097
 No.12 Gauge and smaller	22 gauge	Flat	1	3/32	20	18	110	0 0085
	20 gauge	Flat	1	3/32	30	18	110	0.0132
	18 gauge	Flat	1	3/32	40	18	120	0.0149
	16 gauge	Flat	1	3/32	50	18	120	0.0148
	16 gauge	Flat	1	⅛	70	29	130	0.020
	14 gauge	Flat	1	⅛	85	29	140	0 026
	12 gauge	Flat	1	5/32	115	25	90	0.038

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

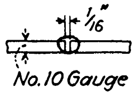
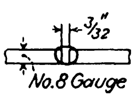
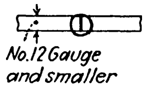
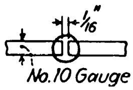
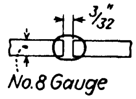
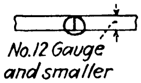
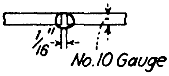
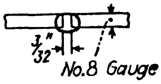
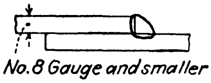
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	10 gauge	Flat	1	5/32	135	25	80	0.051
	8 gauge	Flat	1	3/16	190	27	80	0.073
	22 gauge	Vertical	1	3/32	30	18	100	0 013
	20 gauge	Vertical	1	3/32	30	18	110	0 0132
	18 gauge	Vertical	1	3/32	40	18	120	0 0149
	16 gauge	Vertical	1	3/32	60	20	110	0 018
	16 gauge	Vertical	1	1/8	70	29	130	0.020
	14 gauge	Vertical	1	1/8	80	29	120	0.026
	12 gauge	Vertical	1	5/32	110	26	85	0.040
	10 gauge	Vertical	1	5/32	120	27	65	0.053
	8 gauge	Vertical	1	5/32	130	27	50	0.081
	22 gauge	Overhead	1	3/32	20	18	90	0 011
	20 gauge	Overhead	1	3/32	30	18	110	0 0132
	18 gauge	Overhead	1	3/32	40	18	120	0 0149
	16 gauge	Overhead	1	3/32	40	20	100	0.015
	16 gauge	Overhead	1	1/8	70	29	130	0.020
	14 gauge	Overhead	1	1/8	85	29	140	0 026
	12 gauge	Overhead	1	5/32	110	25	85	0 040
	10 gauge	Overhead	1	5/32	115	25	65	0.055
	8 gauge	Overhead	1	5/32	120	26	45	0.082
	22 gauge	Flat	1	3/32	40	20	90	0.0167
	20 gauge	Flat	1	3/32	40	21	100	0 0201
	18 gauge	Flat	1	3/32	60	22	100	0.023
	16 gauge	Flat	1	3/32	70	22	100	0.0236
	16 gauge	Flat	1	1/8	100	25	100	0 029
	14 gauge	Flat	1	5/32	130	25	100	0.037
	12 gauge	Flat	1	5/32	135	25	90	0.045
	10 gauge	Flat	1	3/16	155	28	90	0.075
	8 gauge	Flat	1	3/16	165	28	90	0.091

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

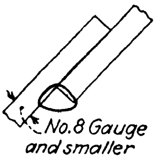
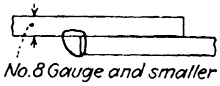
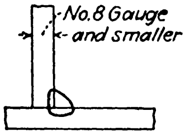
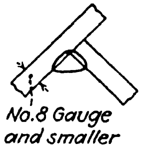
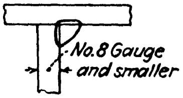
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft
	22 gauge	Vertical	1	3/32	35	21	80	0.017
	20 gauge	Vertical	1	3/32	40	21	100	0.020
	18 gauge	Vertical	1	3/32	60	22	100	0.023
	16 gauge	Vertical	1	3/32	65	22	90	0.025
	16 gauge	Vertical	1	1/8	100	25	100	0.029
	14 gauge	Vertical	1	5/32	130	25	100	0.037
	12 gauge	Vertical	1	5/32	120	26	75	0.049
	10 gauge	Vertical	1	3/16	130	26	90	0.062
	8 gauge	Vertical	1	3/16	140	26	65	0.073
	22 gauge	Overhead	1	3/32	30	18	70	0.0176
	20 gauge	Overhead	1	3/32	40	21	100	0.020
	18 gauge	Overhead	1	3/32	60	22	100	0.023
	16 gauge	Overhead	1	3/32	60	19	80	0.0259
	16 gauge	Overhead	1	1/8	100	25	100	0.029
	14 gauge	Overhead	1	5/32	130	25	100	0.037
	12 gauge	Overhead	1	5/32	120	25	65	0.051
	10 gauge	Overhead	1	5/32	120	25	60	0.058
	8 gauge	Overhead	1	5/32	120	25	55	0.064
	22 gauge	Flat	1	3/32	25	19	80	0.0135
	20 gauge	Flat	1	3/32	30	19	80	0.0155
	18 gauge	Flat	1	3/32	40	21	60	0.031
	16 gauge	Flat	1	3/32	50	21	90	0.0197
	16 gauge	Flat	1	1/8	70	27	60	0.042
	14 gauge	Flat	1	1/8	100	25	60	0.060
	12 gauge	Flat	1	5/32	150	25	60	0.074
	10 gauge	Flat	1	3/16	160	25	60	0.081
	8 gauge	Flat	1	3/16	160	25	50	0.103
	22 gauge	Vertical	1	3/32	20	18	70	0.0133
	20 gauge	Vertical	1	3/32	25	19	70	0.0154
	18 gauge	Vertical	1	3/32	40	21	60	0.031
	16 gauge	Vertical	1	3/32	45	20	75	0.0219
	16 gauge	Vertical	1	1/8	70	27	60	0.042
	14 gauge	Vertical	1	1/8	90	24	60	0.047
	12 gauge	Vertical	1	5/32	140	24	60	0.071
	10 gauge	Vertical	1	5/32	150	24	55	0.081
	8 gauge	Vertical	1	5/32	160	24	50	0.107
	22 gauge	Overhead	1	3/32	18	18	60	0.0142
	20 gauge	Overhead	1	3/32	20	19	60	0.0156
	18 gauge	Overhead	1	3/32	40	21	60	0.031
	16 gauge	Overhead	1	1/8	70	27	60	0.042
	14 gauge	Overhead	1	1/8	85	24	50	0.054
	12 gauge	Overhead	1	5/32	120	24	50	0.072
	10 gauge	Overhead	1	5/32	130	24	50	0.078
	8 gauge	Overhead	1	5/32	130	24	50	0.080

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

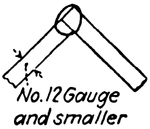
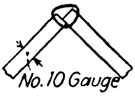
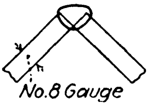
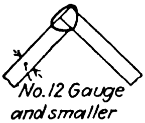
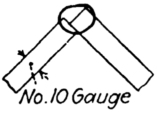
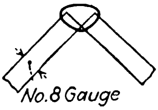
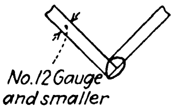
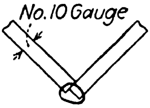
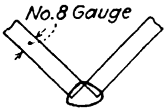
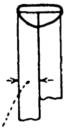
Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	22 gauge	Flat	1	3/32	40	21	240	0.0062
	20 gauge	Flat	1	3/32	40	21	180	0.0104
	18 gauge	Flat	1	3/32	60	24	180	0.0140
	16 gauge	Flat	1	3/32	70	24	200	0.0118
	16 gauge	Flat	1	1/8	90	24	160	0.020
	14 gauge	Flat	1	1/8	90	24	120	0.022
	12 gauge	Flat	1	3/16	125	24	100	0.037
	10 gauge	Flat	1	3/16	140	24	90	0.042
	8 gauge	Flat	1	3/16	175	27	80	0.065
	22 gauge	Vertical	1	3/32	35	21	180	0.0076
	20 gauge	Vertical	1	3/32	40	21	180	0.0104
	18 gauge	Vertical	1	3/32	60	24	180	0.0140
	16 gauge	Vertical	1	3/32	65	24	150	0.0147
	16 gauge	Vertical	1	1/8	90	24	160	0.020
	14 gauge	Vertical	1	1/8	80	28	100	0.022
	12 gauge	Vertical	1	5/32	110	28	95	0.036
	10 gauge	Vertical	1	5/32	130	28	90	0.043
	8 gauge	Vertical	1	5/32	130	28	75	0.051
	22 gauge	Overhead	1	3/32	30	20	160	0.0078
	20 gauge	Overhead	1	3/32	40	21	180	0.0104
	18 gauge	Overhead	1	3/32	60	24	180	0.014
	16 gauge	Overhead	1	3/32	60	21	120	0.0172
	16 gauge	Overhead	1	1/8	90	24	160	0.020
	14 gauge	Overhead	1	1/8	75	25	95	0.024
	12 gauge	Overhead	1	5/32	110	26	95	0.039
	10 gauge	Overhead	1	5/32	125	26	90	0.042

TABLE X.—LAYER SEQUENCES AND DEPOSITION RATES.—(*Continued*)

Type of joint	Thickness of plates	Position of welding	Beads or passes	Electrode size, in.	Arc current, amp.	Minimum arc volts	Actual welding speed, ft. per hr.	Lb. of electrodes per ft.
	8 gauge	Overhead	1	5/32	125	26	65	0.058
	22 gauge	Flat	1	3/32	40	21	200	0.0075
	20 gauge	Flat	1	3/32	40	21	200	0.0094
	18 gauge	Flat	1	3/32	60	23	200	0.0126
	16 gauge	Flat	1	3/32	70	23	200	0.0118
	16 gauge	Flat	1	1/8	80	25	180	0.0171
	14 gauge	Flat	1	1/8	110	27	175	0.018
	12 gauge	Flat	1	3/16	145	28	160	0.023
	10 gauge	Flat	1	3/16	150	28	135	0.029
	8 gauge	Flat	1	3/16	160	28	125	0.031
	22 gauge	Vertical	1	3/32	35	21	180	0.0076
	20 gauge	Vertical	1	3/32	40	21	200	0.0094
	18 gauge	Vertical	1	3/32	60	23	200	0.0126
	16 gauge	Vertical	1	3/32	65	23	190	0.0118
	16 gauge	Vertical	1	1/8	80	25	180	0.0171
	14 gauge	Vertical	1	1/8	80	26	120	0.019
	12 gauge	Vertical	1	5/32	110	26	110	0.023
	10 gauge	Vertical	1	5/32	120	27	100	0.029
	8 gauge	Vertical	1	5/32	120	27	80	0.033
	22 gauge	Overhead	1	3/32	30	18	150	0.0082
	20 gauge	Overhead	1	3/32	40	21	200	0.0094
	18 gauge	Overhead	1	3/32	60	23	200	0.0126
	16 gauge	Overhead	1	3/32	60	20	120	0.0172
	16 gauge	Overhead	1	1/8	80	25	180	0.0171
	14 gauge	Overhead	1	1/8	80	26	120	0.019
	12 gauge	Overhead	1	5/32	110	26	110	0.023
	10 gauge	Overhead	1	5/32	120	26	100	0.029
	8 gauge	Overhead	1	5/32	120	27	80	0.033

Let the following data be taken from the previous tables:

Joint: lap.
Thickness of plate: 3/8 in.
Position: flat.
Electrode size: 1/4 in.
Current: 250 amp.
Minimum arc volts: 30.
Actual welding speed: 40 ft. per hr.
Pounds of electrode per foot of weld: 0.237.

Also, let the following costs be assumed:

Labor: $1 per hour.
Power: 0.02 per kilowatt-hour.

Electrode: \$0.09 per pound.
Efficiency of welding machine: 50 per cent.
Operating factor: 100 per cent.

In computing the cost per foot of deposited weld, the following applies:

$$\text{Cost of labor per foot} = \frac{\text{cost of labor per hour}}{\text{welding speed (feet per hour)}} = \$\tfrac{1}{40} = \$0.0250$$

Cost of power per foot

$$= \frac{(\text{amperes}) \times (\text{volts}) \times (\text{cost per kilowatt-hour})}{(\text{efficiency}) \times (\text{welding speed, feet per hour}) \times (1{,}000)}$$

$$= \frac{250 \times 30 \times 0.02}{0.50 \times 40 \times 1{,}000}$$

$$= \$0.0075$$

$$\text{Cost of electrodes per foot} = (\text{pounds of electrodes per foot}) \times (\text{cost per pound})$$

$$= 0.237 \times 0.09 = \$0.0213$$

$$\text{Total cost per foot} = 0.0250 + 0.0075 + 0.0213 = \$0.0538$$

The above cost is based upon actual welding time only. It does not include any allowance for fatigue of operator, change of electrodes, fit-up, etc. Also, the operating factor has been assumed to be 100 per cent, but a much more accurate figure would be secured by modifying the results by a factor depending on the time the welder actually welds.

For most economical welding, the largest sized electrode permitted by the work should be employed. The larger sized electrodes are desirable because their use results in higher burn-off rates and lower labor cost per pound. Also, since generators have better efficiency when operating at higher currents and since larger electrodes result in higher currents, the larger electrodes result in higher generator efficiency. The values in Table XI bear this out.

TABLE XI.—BURN-OFF RATES AND COSTS

Electrode size, in.	Burn-off rate of electrodes, lb. per hr.	Power cost, dollars per lb. burned off
3/16	3.95	\$0.0387
1/4	7.5	\$0.0363

Larger electrodes bring about lower labor costs per pound of electrode because welding is faster, and there are fewer interruptions for changing electrodes.

Electrode costs are also reduced by using larger electrodes, for the latter cost less per pound and have a much higher burn-off rate. As shown in Table XI, the burn-off rate for a ¼-in. electrode is 7.5 lb. per hr. as compared with 3.95 lb. per hr. for 3⁄16-in. electrodes.

Upon neglecting the variable items of overhead, idling time, and operator fatigue and using the burn-off rate as a basis, the cost of welding per pound of electrode is found to be as follows:

TABLE XII.—COST OF WELDING PER POUND OF ELECTRODE

Item of cost	Electrode size, in.					
	⅛	5⁄32	3⁄16	¼	5⁄16	⅜
Labor	$0.288	$0.227	$0.190	$0.100	$0.070	$0.046
Power	0.043	0.039	0.039	0.036	0.035	0.034
Electrode	0.105	0.095	0.085	0.085	0.085	0.085
Interruptions	0.036	0.024	0.016	0.010	0.006	0.004
Total	$0.472	$0.385	$0.330	$0.231	$0.196	$0.169

In the above the labor is assumed at 75 cents per hour, and the power cost at 2 cents per kw.-hr.

CHAPTER X

WELDABILITY OF VARIOUS METALS BY ARC WELDING

Arc welding is extensively used for joining low-carbon and medium-carbon steels, but it may also be used successfully and economically for welding many other metals.

In arc welding, as in any other fusion-welding process, the metallurgical, chemical, physical, and thermal characteristics of the metals greatly influence their weldability. However, if any of these characteristics are undesirable, they may be corrected by using a proper shielded arc, proper fluxing material, proper electrode or filler metal, proper welding procedure, and in some cases by proper heat-treatment of the metal before and after deposition.

IRON

Wrought Iron.—This metal is a low-carbon (usually about 0.05 per cent carbon) iron containing many elongated particles of iron silicate slag. It is believed that its fibrous structure increases its toughness and its resistance to breaking under bending or under a sudden blow or shock. Iron in this condition is also claimed to be more corrosion-resistant than mild steel.

The shielded-arc welding of wrought iron is handicapped by the slag that accumulates and becomes trapped in the weld, and great care must be taken to melt it out. It is advisable to melt as little as possible of the wrought iron and also to use reversed polarity.

If bare electrodes are used, the welding procedure is comparable with that used for the welding of low-carbon steel. The arcing characteristics of the electrode and the ability to obtain proper fusion between the deposited weld metal and the parent metal are very much like those obtained in welding mild steel.

Welds deposited with mild-steel bare electrodes have a strength approximately equal to that of the base metal. Welds deposited with mild-steel heavily coated electrodes have a strength greater than that of the base metal.

Low-carbon Iron.—This metal, whose carbon content does not exceed 0.06 per cent, is one of the most readily welded of the ferrous metals. Because of this low carbon content, preheating is not necessary and subsequent annealing is not required, unless it is desired to eliminate the residual stresses set up during the welding operation.

Mild-steel heavily coated electrodes should be used for arc welding of low-carbon iron. The usual procedure for the welding of mild steel should be followed. If bare electrodes are used, there will be a reduction in the corrosion-resisting property of the weld and adjacent parent metal.

If the highest quality weld is desired, it is necessary to have complete shielding, for iron with carbon content below 0.15 per cent absorbs gas readily from the atmosphere during welding.

CARBON STEELS

The weldability of steels depends to a great extent upon the amount of carbon present, which may range from 0.04 to 1.65 per cent. In general, the weldability becomes poorer as the carbon content increases. Difficulty is encountered, due to the hardening effect of carbon. A hard, brittle zone of metal forms at the fusion point. The hard zone is caused by the rapid cooling of the molten metal. The cooling takes place because the mass of the work is usually large enough to absorb the heat of the weld very quickly. The action is similar to the hardening of steels by quenching in water or oil.

Other factors affecting the welding characteristics of steels are the additions, impurities, and alloying elements used in the steels.

Low-carbon Steel (up to 0.30 Per Cent Carbon).—Low carbon steels may be readily welded by all forms of the arc-welding process. The resultant welds and joints are of extremely high quality.

If the metallic arc is used, the electrodes may be bare, dust-coated, washed or dipped, or heavily coated.

If the carbon arc is employed, the welding should be done in the presence of a flux or shielding atmosphere. This prevents the formation of brittle welds.

Medium-carbon Steel (0.30 to 0.50 Per Cent Carbon).—Medium-carbon steels can be welded, but the technique and materials used are dictated by the metallurgical characteristics of the base metal. In some cases, preheating and subsequent heat-treatment may be necessary in order to eliminate or reduce the formation of hard and brittle areas in the fusion zone. This is especially true if the steel contains over 0.40 per cent carbon.

Steels of 0.40 per cent to 0.50 per cent carbon should, if possible, be preheated to about 300 to 500°F. This retards the rate of cooling after welding; and if the metal is covered to permit slow cooling, satisfactory results will be obtained. If desired, the previous hardness and toughness may be restored by subsequent heat-treatment. This would involve reheating to the critical temperature, about 1450°F., quenching in water at 70°F., and then slightly reheating to approximately 400 to 550°F., to restore the proper degree of toughness.

Medium-carbon steels may be welded with either bare or coated electrodes. In both cases, the current value must be high enough to give sufficient heat for good penetration and to enable the operator to puddle the metal. The plasticity of a metal increases with the carbon content, and more puddling is necessary to remove gases which must be allowed to escape in order to keep the metal free from porosity. For best results, a coated rod that has been designed for steel of the carbon content of that being welded should be used.

High-carbon Steels (0.60 to 0.90 Per Cent Carbon).—Because of their high carbon content, steels in this class are more difficult to weld than other steels. Hardness and brittleness may result in the fusion zone.

High-carbon steels may be welded by using a special-type coated steel electrode designed to deposit a dense metal having a tough surface of moderate hardness. Mild-steel electrodes may also be used to make welds on these steels. The deposited metal absorbs carbon from the base metal and thus loses considerable ductility. For best results, the parts should be preheated to at least 500°F. before welding. Subsequent heating to 1200 to 1450°F. and quenching in cold water will increase the hardness considerably. Any form of cold-working, such as peening, will harden the surface 10 to 20 per cent.

To be machinable, high-carbon weld metal should be allowed to cool slowly or should be annealed. The machining must consist of grinding to the required dimensions.

Welding on these steels is often done to build up a worn surface to original dimensions or to develop a hard-wear-resistant surface. In such cases, preheating or subsequent heat-treatment are not necessary, unless the carbon content of the parent metal approaches the upper limit.

The required type of electrode should be used with reversed polarity and with arc voltage of 20 to 25 volts. A wide current range may be used and should be adjusted for the particular job on hand.

Size of Electrode, In.	Current, Amp.
3/16	150–225
1/4	225–350

Wide or narrow beads may be deposited. Of course, the usual brushing of the beads must be done before depositing the next beads.

Tool Steels (0.80 to 1.50 Per Cent Carbon).—Tool steels are very difficult to weld. As a matter of fact, it is practically impossible to weld tool steels with satisfactory results for the purpose for which they are usually required.

If tool steels must be welded, three procedures are recommended: (1) The parts are annealed, then preheated and welded with a suitable shielded-arc electrode. This is followed by heat-treatment to restore the desired properties. (2) The parts are preheated, and an austenitic steel electrode is used. The preheating will help to prevent the formation of a hard fusion zone. The austenitic-steel electrode will prevent a hard weld. (3) The parts are preheated, and one or more layers are deposited on the kerf surfaces of the joint with a heavily coated electrode. These layers dilute the carbon content so that the parts can then be more readily welded together. Also, this procedure does not result in a high-carbon weld.

Copper-bearing Steels.—Steels in this class have a low carbon content and contain 0.20 to 0.30 per cent copper. They may be welded in the same manner as ordinary steels of the same carbon content. The welds produced are generally as corrosion-resistant as the base metal.

CAST STEELS

In general, cast steel is of the same chemical analysis as ordinary steel. Low-carbon steel castings can be easily welded if they are properly prepared and reasonably clean and if the ordinary precautions are taken to avoid setting up excessive expansion and contraction stresses in the metal. Special precautions must be taken in the welding of castings having a carbon content above 0.25 per cent or composed of special alloy compositions.

Plain Carbon Steel Castings.—The procedure for welding low- and medium-carbon cast steels should generally be the same as for rolled steel of similar analysis. For best results, a highly coated electrode should be used. Sand inclusions, cracks, porosity, and dirt should be carefully removed from the surfaces to be welded. If the carbon content is low, multilayer welding and high currents may be used. If the carbon content is high, only small-diameter electrodes and low currents should be employed, and in some cases it may be desirable to preheat the work and to retard the rate of cooling.

The carbon arc may be used in place of the metallic arc; to eliminate the absorption of carbon, however, care should be taken not to let the carbon electrode touch the molten metal. By its use, a larger area of metal is molten, and slag and sand can be floated off to good advantage.

The welding of steel castings to rolled steel is easily accomplished, and the procedure is practically the same as for welding rolled steel.

High-manganese Steel Castings.—High-manganese steel contains approximately 12 to 14 per cent manganese and 0.50 to 1.25 per cent carbon. Since it is very tough and hardens on cold-working, it is used where resistance to wear or abrasion is highly essential, as well as where high strength and shock resistance are desired. Examples of this type of application are parts of rock- and ore-crushing machinery, parts of power-shovel buckets, railroad frogs and crossings, and similar parts.

In building up worn parts of high-manganese steel, a shielded-arc process should be used. The characteristics of the deposited weld metal should be approximately the same as that of the parent metal. No water quenching should be used, for this would set up localized cooling strains which often result in checks in the weld and its subsequent failure.

The current set up should be that with reversed polarity. The exact heat depends upon the mass of the parts being welded or built up. Heavy sections require more heat than thin sections. Suggested amperages for various sizes of electrodes are given below, and, as a rule, the lower values should be used as far as possible.

Electrode Size, In.	Current, Amp.
1/8	50- 90
5/32	90–130
3/16	130–170
1/4	170–225

It is essential that the surfaces to be built up be free of all rust and spongy or defective material. Whenever possible, the welds should be deposited in the form of pads, 1/2 to 1 in. wide and preferably not more than 3 in. in length. Though long narrow beads should be avoided, still precautions must be taken to avoid localized heating of manganese steel castings. Thus, the pads should be deposited so that the heat is well distributed throughout the casting. To prevent distortion and possible cracking of the casting, the casting only and not the weld may be cooled with water periodically. The surface of the pad should be hammered or peened immediately after welding or while it is cooling so as to stretch the metal and relieve the cooling strains. The lowest heat possible, consistent with good fusion, should be used. The parent metal should be given time to absorb the heat from the area of welding and to cool between beads. All slag should be cleaned off, and the area where the next pad is to be deposited should be brushed thoroughly.

Heavily coated electrodes of austenitic steel should be used for welding high-manganese steel together, for welding up cracks, and for welding a high-manganese steel to mild rolled steel. This type of electrode gives the weld a high tensile strength.

Alloy-steel Castings.—In general, the procedure for welding alloy-steel castings is the same as that used for rolled alloy steel of the same composition. Of course, the welding properties of the castings are influenced by the number and character of the alloying elements.

Heavily coated electrodes should be used, and the coating should be so proportioned as to influence the weld-metal deposit. The surfaces to be welded should be thoroughly cleaned before welding.

Preheating may be desirable in certain instances, but heat-treatment after welding is completed is desirable in most cases.

CAST IRON

The welding of cast iron is done mainly for the repairing and maintenance of existing machinery and equipment.

Essentially, cast irons are iron alloys containing so much carbon that, as cast, they are not appreciably malleable at any temperature. The carbon content may range from 1.7 to 4.5 per cent. In most cases, an important percentage of silicon is also added.

Carbon may be present in cast irons in two forms: combined or free. Combined carbon is carbon chemically combined with the iron. It tends to make the metal hard, brittle, and nearly nonmachinable. Free or graphitic carbon is carbon in the free state and is mixed with the iron in the form of flakes. Since both the iron and the carbon flakes are not hard or brittle in themselves, the resultant metal is soft and machinable. However, the flakes of free carbon sift among the grains of iron, and thus weaken the metal. The separation of graphite also tends to increase porosity and decrease density.

The amount of combined or free carbon depends on the rate of cooling and the presence in the iron of other elements, such as silicon. When the metal is in the molten state, practically all the carbon is in the combined form. By allowing the casting to cool slowly, nearly all the carbon will pass out of the combined state and separate as flakes of free carbon or graphite. However, if the casting is suddenly cooled, the carbon will remain in the combined form.

If silicon is present, it tends to precipitate graphite during the freezing period. Sulphur tends to keep carbon in solution or combination. Phosphorus causes porosity and segregation of graphite and therefore should be limited closely when density is important.

During the formation of a weld in a cast-iron base, both free and combined carbon go into solution in the molten metal. Upon the removal of the welding heat, there is a quick solidification of the melted iron because of the cooling effect of the comparatively cold mass surrounding the puddle and the cooling effect of the air to which it is exposed. Owing to the sudden cooling, a large amount of combined carbon is retained, and a hard metal in the weld is thus the result. This effect may possibly be reduced by retarding the rate of cooling in some way, such as by preheating.

When preheating is not carried out, care should be taken not to heat the casting too long or too much at the point of welding at one time. Rather, only a small amount of weld metal should be deposited at one time, and sufficient cooling should be done until the job is completed.

Before welding cast iron, a careful study of the job should be made to prevent uneven expansion or contraction of the casting. When one part of a casting is heated, the part expands, and considerable strain may be thrown on some other part. Since the metal has low ductility and will not stretch, the strain may be sufficient to break the unheated part.

When cast iron is welded with a filler metal of different composition from the base metal, great consideration must be given to the fact that the coefficients of expansion of the two metals may also differ from one another. If so, cracks may result, or large internal strains or stresses may be set up.

Since molten or even red-hot iron oxidizes very readily when exposed to air, a film of iron oxide may form during welding. If this film is mixed with the weld or trapped between layers, the resultant weld will be weak and nonhomogeneous.

Castings should be properly grooved before welding. This may be done by chipping, grinding, or even cutting with a gas torch. When the casting contains a large amount of free carbon, a film of graphite may form upon the surfaces to be welded, owing to the chipping or grinding action, especially to the latter. If fusion welding is to be done, this film will not interfere with the weld; but if brazing is to be done, the film may interfere with the adhesion of the filler metal to the base metal, and thus a weak weld may result. The film should be removed by sandblasting, wire brushing, or heating with a gas torch.

Gray Iron.—Gray irons are those cast irons which contain a considerable amount of free carbon. The appearance of their fracture is grayish or blackish and coarsely crystalline.

In welding gray cast iron, it is usually necessary to preheat to a dull red heat to avoid stresses. Gray-iron castings may be welded hot and then permitted to cool slowly so as to maintain their characteristic gray-iron structure. Preheating may be avoided only if the structure of the weld metal is of little importance.

Welding with Steel Electrodes.—Gray cast iron may be welded with a metallic arc using steel electrodes, but care should be taken in regard to (1) the contraction of the weld metal (steel) after deposition and (2) the absorption of carbon by the weld metal and rapid cooling which result in hard weld metal.

In going from a molten state to a cool state, the shrinkage of contraction is greater for steel than for cast iron. Thus, when the molten weld steel from a steel electrode is deposited, a residual strain is set up in both the weld metal and the cast iron. Actually, the steel weld metal exerts a pulling action on the cast iron. Since cast iron is weaker than steel, the usual occurrence, especially when the bead of weld metal is long, is a break in the cast iron just behind the line of fusion.

Since strain is cumulative, it is evident that the greater the length of the weld in a straight line the greater the strain. At the same time, the cumulative effect may be reduced by depositing beads in a curved line (see Fig. 192). Another way is to deposit weld metal in short lengths and allow each bead to cool (see Fig. 193). A third method is to peen the deposited weld metal while still hot and before it has had a chance to cool and contract. The peening causes the weld metal to stretch. Perhaps the best procedure would be to use a combination of the three methods.

When steel weld metal is deposited on a large casting, there is a quick cooling of the weld metal and the cast iron in its vicinity. Since the deposited metal absorbs carbon from the cast iron during welding, it becomes extremely hard when cooled quickly. At the same time, the molten cast iron, being also quickly cooled, has its own combined carbon increased, and the casting becomes harder and more brittle. Therefore, in such cases, hard and unmachinable material is formed. If machining is necessary, several methods may be used to make the weld metal and weld area in the cast iron machinable. In one method, the entire casting is heated; or if expansion causes no difficulty, the weld or adjacent parts only are heated to a dark cherry red and allowed to cool slowly by covering with a heat-retention material such as asbestos or sand.

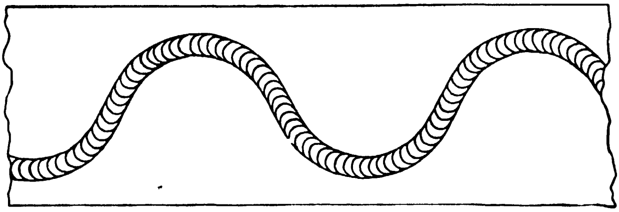


FIG. 192.—A method of relieving cumulative strains on cast iron: depositing weld metal in curved lines.

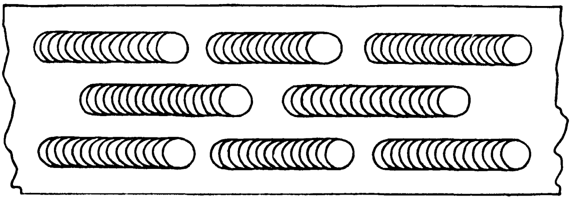


FIG. 193.—Sequence of short welds used to help relieve cumulative strains set up during deposition.

In general, the weld metal deposited by the metallic-arc process in cast iron is much stronger than the cast base metal. When steel electrodes are used, the weld metal is three to four times as strong as the casting.

Coated electrodes of ⅛-in. size are designed and used to keep the required heat down to a minimum, thus reducing the resultant hardness. The electrode is made positive and the work negative. A current of approximately 80 amp. is used. This apparently too low current is employed only to satisfy the requirements of cast-iron welding which make the use of higher heat inadvisable.

Welding with Chrome-Nickel Steel Electrodes.—The use of a heavily coated metal electrode having 18 per cent chrome, 8 per cent nickel, and a low carbon (0.07 maximum) content may be found to give a firmer bond of weld metal with cast iron than the use of a mild-steel electrode will. Light peening, while the welding bead is still warm, may be used to help relieve the contracting strains.

Welding with Carbon Arc.—The welding of iron castings may be done by using a carbon arc and a cast-iron filler rod. In welding in the flat position, fairly machinable welds may be produced by proper manipulation of the arc and filler rod. This may be attributed to the fact that the carbon arc being played about the work permits slower cooling of the deposited and base metal. Also, the oxide may be floated out of the molten metal, the hard spots which would cause trouble during machining operation being thus eliminated. Dehydrated borax flux is sometimes used, for it enables the operator to float out some of the undesirable impurities.

The cast-iron filler rod used with this method is usually of far better quality than the base metal. Thus, the tensile strength of the weld metal may be higher than that of the casting.

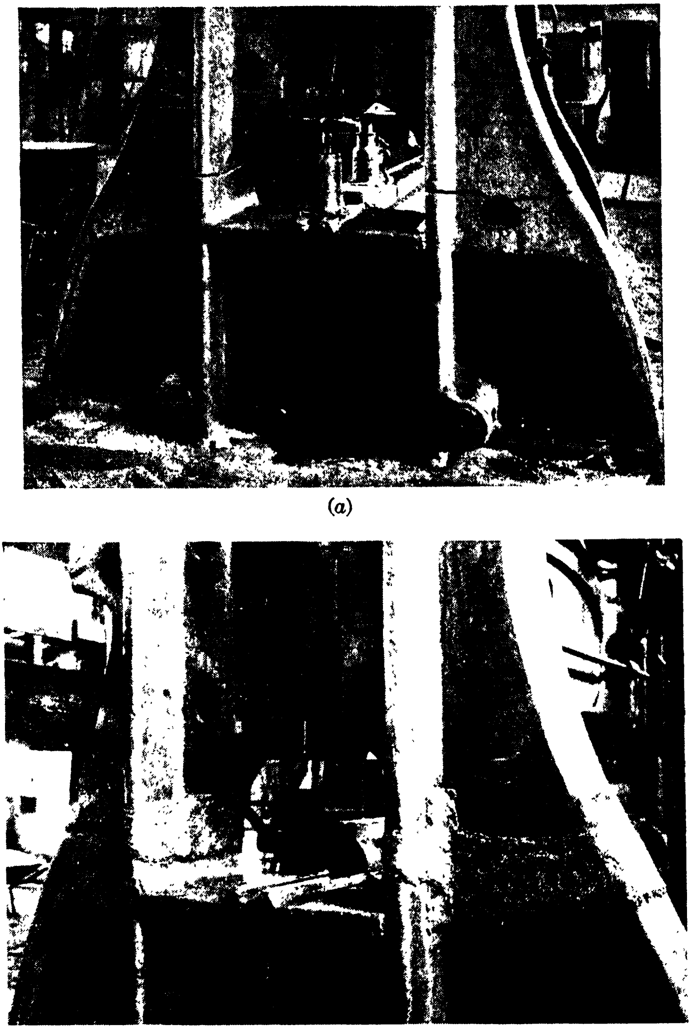
Welding with Cast-iron Electrodes.—When cast iron is welded by the metallic-arc process with cast-iron electrodes, the casting must be preheated in order to receive the molten metal from the end of the rod as fast as it comes off. Reversed polarity is always used with this method. This process is not widely used, for it permits too rapid cooling, thus giving a hard and unmachinable weld.

Welding with Nonferrous Electrodes.—Unlike steel rods, nonferrous alloys (electrodes) do not harden appreciably when deposited in a cast-iron base metal, for the nonferrous alloys do not absorb carbon from the casting. Welds made by this process are therefore machinable. However, the cast iron hardens in the section adjacent to the line of fusion, owing to the quenching action of the mass of cold metal behind it.

The shielded-arc bronze type of electrode is one of the most widely used nonferrous electrodes. The resultant weld is soft and has a good tensile strength.

Studding.—It has been seen that the chilling action of cast iron increases the combined carbon, which makes for greater hardness and brittleness and weakens the strength of cast iron just behind the line of fusion. Studding is a mechanical method of strengthening welds in cast iron, provided that they are of sufficient thickness (see Figs. 194 and 195).

The cast iron should be veed and drilled and tapped along the vee so that the steel studs, approximately ¼ to ⅜ in. in diameter, may be screwed in the casting. The studs should be of sufficient length to be screwed into the casting to a depth of at least the diameter of the studs and still project about 3/16 to 1/4 in. above the cast-iron surface.



(*a*)

(*b*)

FIG. 194.—Cracked cast-iron end frame repaired by means of studding. (*Courtesy of The Lincoln Electric Company.*)

The cross-sectional area of the studs should amount to about 25 to 35 per cent of the area of the weld surface. Usually, one or two beads are deposited around each stud, ensuring fusion both with the stud and with the cast-iron base. If possible, welds should not be deposited in straight lines; rather, they should be deposited intermittently, and each bead peened before cooling.

In some instances, it may be practical and more desirable to shape out grooves in the casting with a roundnose tool instead of studding.

Malleable Iron.—White cast iron which has been treated so that the carbon content of the casting occurs in uniformly distributed particles, called "temper carbon," is known as *malleable iron.* With carbon in this condition, the malleable castings are not nearly so brittle as gray cast iron castings.

Malleable iron has physical properties that are a cross between those of cast iron and those of steel forgings. Its tensile strength is much higher than that of gray cast iron, its ductility is much better, its softness greater, and it may be bent to a certain degree.

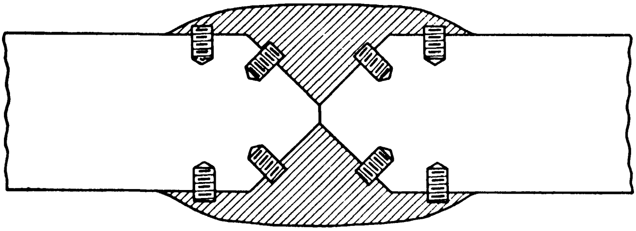


FIG. 195.—Usual procedure of studding for cast iron welding.

During welding, the carbon is still present, but in a different form; and when the casting is heated and then quickly cooled, the effect of the heat-treatment or annealing in the vicinity of the weld is destroyed.

In welding malleable iron, the same procedure as in welding gray cast iron applies, and thus the same precautions should be taken.

The common practice followed in many malleable iron foundries is to weld small defects with the metallic-arc process. The casting is then put through an annealing oven, so as to overcome the changes in structure due to welding. In the field, this may not be practical or it may be almost impossible.

In general, fusion welding of malleable iron is regarded as unsatisfactory, even when the castings are remalleableized afterward. For this reason, brazing is generally used to repair malleable castings.

Alloy Cast Irons.—Sometimes, cast irons are alloyed with special elements, such as nickel, to obtain an improved and more uniform structure, hardness, wear resistance, strength, and machinability.

The welding procedures for most alloy cast irons are essentially the same as for gray cast irons. The filler metal should be of the same alloy content as the base metal. If this is not available, the weld should be made with a high-quality gray-iron rod.

LOW-ALLOY HIGH-TENSILE STEELS

All steels in this class are readily weldable. Their alloy content is not much greater than that of ordinary mild steel, and it is considerably less than that of many alloy steels. They have higher physical properties than carbon steels and usually possess higher resistance to atmospheric corrosion.

If filler metal must be added during welding, it need not have the same composition as the base metal, provided that it has the same physical characteristics. If resistance to corrosion is a factor, however, the filler metal should have a composition similar to that of the base metal.

For metallic-arc welding, a shielded-arc type of electrode should be used.

To develop the required physical properties, such as strength, ductility, resistance to shock, and resiliency, it may be desirable to heat-treat. The recommended heat-treatments for these alloy steels are given below, under each heading.

Plain Nickel Alloy Steel.—If the carbon content of 3 to 3½ per cent nickel alloy steels does not exceed 0.25 per cent, no heat-treatment is necessary. However, if it is in excess of 0.25 per cent, the work should be preheated to 300 to 600°F. Also, since they tend to air-harden, these steels should be cooled very slowly in order to retain the wanted physical properties.

Nickel-Copper Alloy Steel.—These steels contain 1 to 2 per cent nickel, 1 to 1.6 per cent copper, and not over 0.25 per cent carbon. Except when 0.20 per cent carbon or more is present, no preheating is necessary for welding. If desirable, the preheat should range from 250 to 300°F.

Manganese-Molybdenum Alloy Steel.—The steels in this group contain 0.60 to 1.60 per cent manganese, 0.30 to 0.70 per cent molybdenum, and less than 0.25 per cent carbon. No preheating is necessary unless the carbon content is in the higher end of the range or the sections to be welded are heavy and difficult. In these cases, it may be advantageous to preheat to 250 to 300°F.

Carbon-Molybdenum Alloy Steel.—These alloy steels contain 0.30 to 0.60 per cent manganese, 0.30 to 1 per cent molybdenum, and not more than 0.25 per cent carbon. As in the previous alloys, no preheating is required under ordinary conditions. However, if the molybdenum content is over 0.50 per cent or if the carbon content approaches or exceeds 0.25 per cent, it may be desirable to preheat to 350°F., in order to obtain the best results.

Carbon-molybdenum steels are used frequently where high pressure (up to 2,000 to 2,500 lb. per sq. in.) and high temperature (up to 800 or 900°F.) are encountered. They have an ultimate tensile strength of about 75,000 lb. per sq. in.

If the thickness of the metal is greater than ⅜ in., it may be advisable to stress relieve by heating to a temperature of 1200 to 1250°F. The rate of cooling should be from 200 to 250°F. per hour down to 150 to 200°F., at which point cooling may be done in still air.

Nickel-Chromium Alloy Steel.—Several analyses are embraced in this classification. The nickel content ranges from a low of 1 per cent to a high of 3½ per cent; the chromium from 0.40 to 1.75 per cent; and the carbon from 0.20 to 0.55 per cent. For safe welding, these steels should be preheated. A preheat of 200 to 300°F. is all that is necessary for the lower range tensile steels having a maximum of 0.20 per cent carbon. With the higher carbon contents that accompany the increased percentages of nickel and chromium, a preheat of 600 to 800°F. is considered desirable and should be followed by slow cooling. A preheat temperature of 900 to 1100°F. may be even more desirable for the highest carbon, nickel, and chromium contents.

Chromium-Molybdenum Alloy Steel.—The steels in this classification contain 0.25 to 0.55 per cent carbon, 0.15 to 0.25 per cent molybdenum, and 0.50 to 1.10 per cent chromium. They are designed especially for high-temperature service. Owing to the high chromium content, a considerable degree of preheat is required, ranging from 300 to 800°F. Slow cooling is also desirable after welding operations.

Chromium-molybdenum steel, when not heat-treated, has a tensile strength of about 80,000 lb. per sq. in.; but when properly heat-treated, it has a tensile strength ranging from 125,000 to 160,000 lb. per sq. in. Deposited welds also nearly double their strengths upon heat-treatment.

Welds having a tensile strength of 60,000 to 70,000 lb. per sq. in. before heat-treatment can be produced in these steels, by using a carbon arc with a piece of the base metal as filler material. After proper heat-treatment, these welds will show a tensile strength of 125,000 to 160,000 lb. per sq. in. Although this type of welding procedure gives the best results for the arc welding of chromium-molybdenum steel, it is not so fast or so easy to handle as the metallic shielded-arc process. For this reason, chromium-molybdenum steel is welded with the shielded-arc process, a shielded-arc electrode being used.

By using a metallic electrode having a heavy extruded coating, welds can be produced in chromium-molybdenum steels having a tensile strength of 60,000 to 80,000 lb. per sq. in. before heat-treatment and of 125,000 to 150,000 lb. per sq. in. after heat-treatment.

The thorough mixture of base metal with deposited metal in the weld is one of the main reasons for the higher tensile strength of weld metal in chromium-molybdenum steel.

The welding procedure for chromium-molybdenum steel is the same as that for mild-rolled steel. Some recommended current values for the welding of type S.A.E. 4130 and X4130 steels follow:

Size of electrode, in.	Current, amp.	Arc voltage, volts
1/8	65–120	23–26
5/32	80–160	23–26

After welding with the electric arc, the heat-treatment consists in normalizing to 1650 to 1750°F. and cooling slowly in the furnace below red heat, heating to 1550 to 1655°F. and quenching in light oil, and drawing 950°F. or a like temperature to secure the desired hardness.

Nickel-Chromium-Molybdenum Alloy Steel.—This steel contains 1.5 to 2 per cent nickel, 0.20 to 0.40 per cent molybdenum, and 0.30 to 0.90 per cent chromium. It is widely used in industry, but not many data are available about its heat-treating properties.

Nickel-Molybdenum Alloy Steel.—These steels have a low carbon content; the nickel ranges from 1.65 to 3.75 per cent and molybdenum from 0.20 to 0.30 per cent. They have not been welded very widely, and thus not very many desired data are available.

Chromium Alloy Steel.—There are two analyses of this type of steel. In the first, there are present a maximum of 0.25 per cent carbon and of 0.60 to 0.90 per cent chromium; in the second, 0.35 to 0.55 per cent carbon and 0.80 to 1.10 per cent chromium. Before welding these steels, it is necessary to preheat to a temperature ranging from 200 to 800°F.

Chromium-Vanadium Alloy Steel.—This steel is used in two ranges of carbon, one up to 0.25 per cent maximum and the other from 0.25 to 0.55 per cent. In both instances, the chromium content is 0.15 to 0.20 per cent. For satisfactory welding, these steels must be preheated to 200 to 800°F.

Manganese Alloy Steels.—These steels contain 1.6 to 1.9 per cent manganese and 0.25 to 0.55 per cent carbon. To obtain satisfactory results, a preheat of 400 to 800°F. is essential.

STAINLESS STEELS

The stainless alloys may be divided into two groups, with respect to welding: (1) stainless irons which contain 3 to 28 per cent chromium, with or without nickel, and which are essentially magnetic; (2) stainless steels which contain chromium and nickel, with or without any additions of molybdenum, manganese, columbium, silicon, or titanium.

Chromium Alloys.—The alloys in this group, known as "stainless irons," contain 12 to 28 per cent chromium as the essential alloy constituent. These alloys have a tendency toward grain growth in and near the weld, especially if the chromium content is in the higher ranges. This results in undesirable brittleness. The tendency toward grain growth may be alleviated by small additions of nitrogen.

The most widely used stainless iron is probably that containing 15 to 18 per cent chromium and a maximum of 0.10 per cent carbon. This alloy is readily weldable; and if properly heat-treated (to 1450°F., slowly cooled), it possesses satisfactory physical properties in both weld and plate and has sufficient corrosion resistance.

Stainless irons may be successfully welded by electric-arc methods, especially by the metallic arc. Coated electrodes should be used. The metallic core of the electrode should have a composition similar to that of the base metal, preferably with slightly higher chromium content, in order to provide for the metal loss during welding.

Chromium-Nickel Alloys.—What is commonly known as "stainless steel" is the most widely used alloy of the iron, chromium, and carbon group. Its carbon content is such that the alloy hardens upon quenching.

The stainless properties of these alloys are due to the ability of chromium and nickel to mix with iron to form a solid solution which is resistant to various corrosive media. To ensure the stainless properties, it is essential that there be sufficient chromium and nickel, or chromium, present in solid solution. As a group, these alloys do not harden with heat-treatment, do not require special heat-treatment other than that received at the mill to develop stainless properties, and lend themselves to deep drawing and other forming operations.

Many types of stainless steel are sold by different companies under different trade names. Most of them have been classified and given standard type numbers by the Iron and Steel Institute (I.S.I.).

The most widely used stainless steel is the so-called 18-8 variety, that is, one having approximately 18 per cent chromium and 8 per cent nickel. The carbon content usually ranges between 0.08 and 0.20 per cent. It has a tensile strength of about 85,000 to 95,000 lb. per sq. in. Stainless steels are also furnished commercially in ratios of 25-12 and 25-20

For the regular 18-8 alloy to resist corrosion to its fullest extent, it must be in its annealed condition, in which the carbon is present in solid solution. Unfortunately, when this alloy is heated in the range between 800 and 1300°F. it undergoes a structural change that is detrimental to its corrosion-resistant properties, although its mechanical properties are not affected to any appreciable extent. This is attributed to the precipitation at grain boundaries of very fine films of chromium-rich carbides, containing as much as 90 per cent chromium taken from the layer of metal immediately adjacent to the grain boundary. This, of course, means that the chromium content of the metal adjacent to the grain boundaries may be so reduced that its resistance to corrosion will be seriously impaired. "Carbide precipitation" is the term applied to this phenomenon. The type of corrosion that is likely to take place is commonly known as "intergranular corrosion." The heating between 800 and 1300°F. necessary to produce this change is easily realized during welding.

There have been various methods devised to reduce or prevent intergranular corrosion. To obtain complete immunity, the welded article may be heated to about 1950°F. and then rapidly cooled by quenching; but this treatment may cause distortion of finished parts, and in case of large welded structures it may be impossible. Another method is to reduce the carbon content of the alloy to such a low value that no carbide is precipitated. An 18-8 alloy with a carbon content of 0.02 per cent is not susceptible to intergranular corrosion; but the cost of production of such an alloy is very high, and it is not available commercially. However, to minimize carbide precipitation, 18-8 with 0.08 per cent carbon maximum is usually specified for welded structures, and electrodes that contain 0.05 to 0.07 per cent carbon are used.

Also helpful, it has been found, is the addition of an alloying element that has a greater affinity for carbon than chromium. Titanium and columbium are often used as stabilizing elements.

In welding stainless steels, it must be kept in mind that their coefficient of expansion is high and that their heat conductivity is low. Thus, in setting up any job for welding, allowance must be made for expansion and contraction. In many cases, it is advisable to have proper fixtures for holding the work in place during welding.

Because of the low thermal conductivity, the heat of the arc is more localized and does not travel back into the plate, and thus less heat may be used in welding.

The shielded-arc process with heavily coated electrodes should be used. The electrode core should be approximately of the same analysis as the plate, and columbium or titanium should be used as a corrosion preventive. Since the electrical resistance of a stainless steel electrode is high, short electrodes should be used to avoid overheating. Reversed polarity should also be used.

The preparation of the work to be welded should be as for ordinary metal-electrode welding of mild steel. Surfaces should be clean and free of scale. After welding, there may be a discolored zone on both sides of the bead, due to scale formed at high temperature. Since this discolored zone of base metal may not be so corrosion-resistant as the rest of the metal, this scale should be removed by grinding, pickling, or some similar process if maximum corrosion resistance is to be obtained. When multiple layers are used, the slag should be thoroughly cleaned off the preceding bead before depositing the next.

When welding 18-8 stainless steels in the *flat position*, the following amperages and voltages are suggested:

Size of electrode, in.	Current range, amp.	Arc voltage, volts
5/64	25- 60	20-24
3/32	30- 70	23-26
1/8	45- 95	23-26
5/32	80-135	23-26
3/16	100-165	23-26
1/4	140-225	23-26

When welding 18-8 stainless steels in the *vertical* or *overhead position*, the following amperages and voltages are recommended:

Size of electrode, in.	Current range, amp.	Arc voltage, volts
5/64	25- 35	20-24
3/32	30- 45	23-26
1/8	45- 80	23-26
5/32	80-100	23-26

The manipulation of the arc, starting, finishing, weaving of beads, and cleaning of passes are accomplished as in the shielded-arc process for mild steel.

Stainless-clad Steel.—Stainless-clad steel is a ply material having a thin surface of true stainless steel on a foundation of soft or mild steel. The stainless-steel layer usually constitutes 10 to 20 per cent of the thickness of the plate or sheet, and either one or both sides may be coated. Such clad steel retains the corrosion-resisting advantages of solid stainless steel, but at a reduced cost. It is particularly advantageous in those applications where only one side of the plate or sheet needs to be stainless.

Stainless-clad steels are produced so that they can be bent, spun, and deep-drawn without any damage. As a rule, the bond between the mild steel and the stainless "cladding" is strong enough to withstand not only the stresses incidental to fabrication of the finished product, but also the great stresses due to a difference of expansion between the stainless facing and the backing when heated and cooled repeatedly.

If the metallic-arc method is used for welding the stainless side of the stainless-clad steel, the electrode should be positive and the work negative. The electrodes should be of the proper analysis for the cladding being welded. If the cladding is of the 18 per cent chrome 8 per cent nickel type, it will be found that an electrode having 24 per cent chrome and 12 per cent nickel offers a corrosion resistance equal to or superior to that of stainless steel. However, even the 18-8 electrode will give satisfactory results. As a rule, in welding cladding, the electrode should have a higher alloy content than that of the material being welded. The amount of current used for welding the stainless-steel surface should not be excessive. If the amperage is too high, there will be an overheating of the sheet in the weld area, as well as overheating of the electrode. Extremely low amperage will result in slag inclusions and lack of fusion. The amperage required for each diameter of electrode is affected by prevailing conditions, analysis, type of coating, amount of coating, length of electrode, etc.

The required sizes of electrodes for various sheet and plate thicknesses are approximately as follows:

Sheet Thickness, In.	Electrode Size, In.
Under 1/16	5/64
1/16–1/8	3/32
1/8–1/2	1/8
3/16–1	5/32

Whenever possible, it is advisable to use chill bars in welding the lighter gauges of stainless-clad steel, for it is necessary that the weld and adjacent metal cool quickly. In the case of heavy plates, this is not necessary, for the mild-steel backing actually acts as a chill.

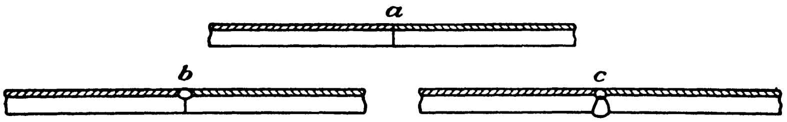


FIG. 196.—Recommended procedure for welding stainless-clad steel, 10 gauge and thinner.

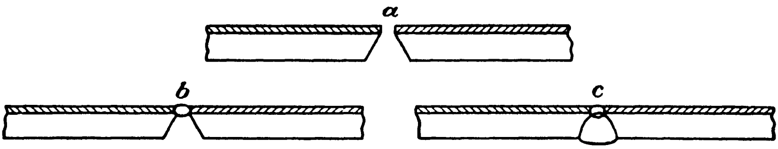


FIG. 197.—Recommended procedure for welding stainless-clad steel, 10 gauge to 3/8 in.

There is little need for heat-treating after welding, and it is not necessary to peen stainless welds. Provided that the proper electrodes and the proper welding technique are employed, little or no slag inclusion or porosity will be encountered. Also, no porosity results in welding over steel with a stainless electrode or over stainless steel with a high-grade shielded-arc type of mild-steel electrode.

The mild-steel side of stainless-clad steel should be preferably welded with multiple beads to avoid overheating the surface.

The cost and the quality of the weld deposits are greatly influenced by the design and preparation for welding. If the proper design is used, welding labor may be reduced materially, and the amount of stainless-steel electrode kept to a minimum. Some recommended procedures for welding various thicknesses are shown in Figs. 196 to 200.

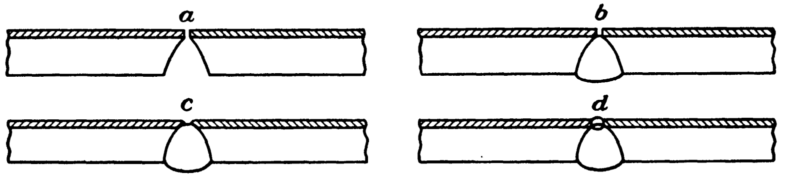


FIG. 198.—Recommended procedure for preparation and welding of stainless-clad steel, ½ in. and heavier, when plate planing equipment is available.

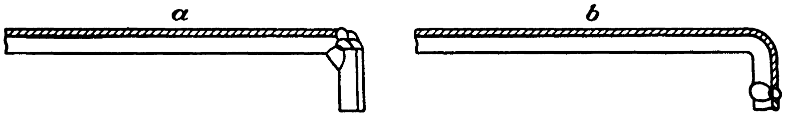


FIG. 199.—Procedure for welding right-angle intersections of stainless-clad steel, as in tank construction.

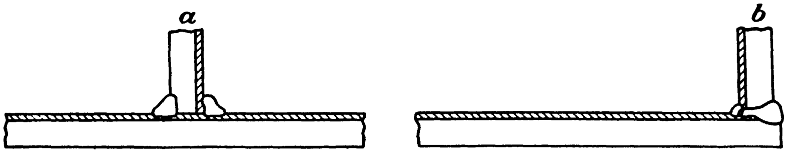


FIG. 200.—Joints used in stainless-clad steel to reduce contamination of cladding due to iron pickup.

COPPER AND COPPER ALLOYS

In commercial importance, copper is second only to iron and steel. It has a distinctive red color and possesses combined strength and ductility, as well as high heat and electrical conductivity. It also has excellent corrosion-resisting properties.

Copper is often alloyed or mixed with other metals such as zinc, tin, nickel, silicon, aluminum, manganese, iron, beryllium, cadmium, chromium, and lead. The principal alloys are classified as Muntz metal, yellow brass, cartridge brass, low brass, rich low, or red, brass, silicon brass, commercial bronze, gilding metal, Tobin bronze, naval brass, manganese bronze, phosphor bronze, silicon bronze, aluminum bronze, nickel silver, and cupro-nickel.

Electrolytic, Tough-pitch, and Lake Copper.—Electrolytic copper contains about 0.03 to 0.07 per cent oxygen in the form of cuprous oxide. This small amount of oxygen has little effect upon the electrical or physical properties of the metal, but it is troublesome for welding purposes.

Cuprous oxide has a slightly lower melting point than pure copper. Therefore, when electrolytic copper is heated near its melting point, the cuprous oxide fuses and may cause embrittlement.

Upon welding electrolytic copper, the cuprous oxide, increased by the welding process, spreads out along the grain boundaries so that a small amount of it will form a serious line of weakness. As a result, even if the weld is perfect, the strength of the welded joint is much less than that of wrought electrolytic copper.

Cuprous oxide is also reduced by hot hydrogen gas; and when this takes place, there is again a material reduction in weld strength.

Electrolytic copper may be welded by metallic arc, if a suitable shielded-arc electrode is used, or by carbon arc and filler metal. Where practical, the automatic carbon-arc process should be used in preference to the manual process, because of the smooth and dense weld thus produced.

The physical characteristics required in the welded structure determine the composition of the filler metal. A pure copper or cadmium copper filler metal may be used if the weld must have a low electrical resistance. If ductility and strength are the main requirements, the filler metal may be silicon copper, 10 per cent tin-phosphor-bronze, or Everdur. A fluxing material should be used with Everdur. Since molten copper absorbs hydrogen very rapidly, steam or moisture-producing fluxes must be kept away from the arc.

On light copper, there is usually no need of preheating; but on heavy sections, preheating may be necessary because of the high conductivity of the metal. The preheating may be done by rapidly moving a carbon arc over the area to be welded. After starting to weld and as the heat builds up in the section being welded, a lower current may be required.

To facilitate welding, the work should be clamped to a backing of copper, carbon, or graphite. If this is not practical, the sheets should be elevated so that the bottom of the joint and the work table have a space between them. Thus, a small amount of excess metal may be deposited on the underside of the metal.

Cleanliness of the joint is necessary to ensure a good weld. Where oxides are present, a warm 10 per cent sulphuric acid solution may be used to clean the joint.

When the manual carbon arc is employed, the plate edges should be spaced about ⅛ in. apart, and a filler rod of the proper size should be used. The rod should be about 20 per cent heavier than the thickness of the metal being welded. The resulting quality of the weld depends, to a great extent, upon the speed of welding. For best results, the welding should be done at high speed. For instance, a better weld is obtained at a welding speed of 20 in. per min. on a ¼-in. plate with 600 amp. at 40 volts than is obtained at 7 in. per min. with 200 amp. High voltage and a long arc must be used so as to allow the carbon monoxide produced by the carbon arc to combine with oxygen in the surrounding atmosphere instead of entering into combination with the copper to cause excessive porosity of the weld.

Deoxidized Copper.—To avoid the effects of cuprous oxide, the copper may be deoxidized by introducing phosphorus, manganese, silicon, or boron. Deoxidized copper welds much more easily than oxygen-bearing copper, and, at the same time, its welded joints are much stronger and much more ductile. It should be used in all cases where the welded structure is to be subjected to severe service. It is not subject to hydrogen embrittlement; and although its thermal conductivity is somewhat lower than that of oxygen-bearing copper, this property is still high enough to require a high input of welding heat.

The procedure for arc welding of deoxidized copper is similar to that for oxygen-bearing copper. However, when the thickness of the material exceeds $\frac{1}{8}$ in., the metallic-arc process is not advisable. The carbon-arc process produces satisfactory results.

Red Brass, Low Brass, Commercial Bronze, Ounce Metal, and Hydraulic Bronze.—These materials constitute the most common commercial alloys of copper. They are essentially alloys of copper and zinc, although small amounts of other metals are sometimes added to alter or improve some of the properties. The addition of the zinc results in a material that is cheaper, harder, and stronger than copper; at the same time, it retains the malleability, ductility, and corrosion resistance of copper.

The alloys in this group, in general, are quite weldable, except that, if the weld metal is superheated, trouble is experienced with zinc vaporization. They can be welded manually by employing a suitable electrode or automatically with the carbon arc. The arc should be played on a zinc-free filler metal as applied in flat butt or lap welding, so that the base metal is not fused but is heated by the highly superheated weld metal. By doing this, serious difficulty from zinc vaporization can be avoided.

Brazing, Spring, Admiralty, Commercial, Alpha, and Yellow Brass.—The materials in this group are brasses of low melting range and heat conductivity. They are not so easily welded by arc as the materials in the preceding group, and the application of the metallic arc should be avoided on account of the vaporization of the zinc. Carbon-arc welding may be applied, provided that a suitable technique is employed in which the arc is directed toward the zinc-free metal rods.

Muntz Metal, Tobin Bronze, Naval Brass, Manganese Bronze, and Extruded Brass.—These materials have welding properties similar to those of the yellow-brass group. They possess high strength, good corrosion resistance, and good hot-forging and extruding qualities. They are not commonly welded by the metallic arc; but they may be welded by the carbon arc, with a long arc, provided that the thickness of the material does not exceed ⅛ in.

Nickel Silver.—These alloys are used for artistic purposes and to some extent by reason of their corrosion resistance. Because of the nickel content, they have lower thermal and electrical conductivity and thus are easier to weld. Any nickel oxide that may tend to form can be checked to a certain extent by employing a suitable flux.

Satisfactory carbon-arc welds can be made if phosphor bronze electrodes are used. For position welding, silicon copper electrodes should be used. They may be metallic-arc-welded, and by employing coated electrodes it is possible to obtain satisfactory strength and color match. With this process, however, the zinc tends to vaporize from the base metal.

Phosphor Bronze.—Bronze is an alloy consisting mainly of copper and tin. Phosphor bronze is an ordinary bronze to which has been added a small percentage of phosphorus for deoxidation purposes. But most of the metals in this group do not contain sufficient phosphorus to ensure thorough deoxidation; as a result, tin oxides are likely to be developed in the weld metal. The metal tends to be hot-short and is subject to shrinkage cracks under certain conditions, especially when there is a wide-spreading heat and a slow cooling.

These alloys may be satisfactorily arc-welded. With the carbon-arc process, the arc should be played on the weld metal in order to avoid the formation of tin oxides in the base metal. With this process, contraction is kept to a minimum by the concentrated application of heat. The use of a flux is desirable but not entirely necessary. The welding should be done only in a flat or nearly flat position. With the metallic-arc process, a flux-coated phosphor bronze electrode should be used in order to reduce the tendency toward oxidation of the tin.

Copper-Silicon Alloys.—The alloys in this group consist of copper to which has been added small percentages of silicon and manganese or tin. Although commonly carrying about 96 per cent copper, they have low heat conductivity and develop a continuous protective film on the metal the instant it is melted. This film aids in holding the metal in place during fusion welding. In order to keep the grain size small, it is desirable to have rapid solidification and rapid cooling. A fine grain structure is important because it results in suitable tensile strength and ductility. Jigging of the work is often done in order to hold the edges rigid during welding. Peening the metal when cold or nearly cold improves its tensile strength and ductility.

Most important among these alloys are *Everdur* and *Herculoy.* Everdur contains 1.5 to 4.5 per cent silicon and 0.25 to 1.1 per cent manganese. Herculoy contains 3 to 3.25 per cent silicon and 0.5 per cent tin.

Everdur is one of the most weldable of all copper alloys. The highest strength and soundness may be obtained. The intense heat of the arc does not impair it, and only a slight reinforcement is required to develop the full strength of the base metal. It can be easily welded by either metallic or carbon arc.

When the metallic-arc process is used, an electrode of the same composition as the base metal is generally used. The amount of heat required is determined by the size of electrode and the thickness of the work to be welded. Reversed polarity should be employed. The edges of the joints to be united should be clean and free of scale, for scale prevents proper fusion. A flux consisting of 90 per cent fused borax and 10 per cent sodium fluoride gives satisfactory results in welding with a metallic arc.

Carbon-arc welding of Everdur requires the same procedure as metallic-arc welding, with the exception that a shorter arc is held and straight polarity is used. If any additional filler metal must be employed, it should have the same composition as the base metal.

Everdur may also be welded by automatic carbon arc. The welds have a tensile strength equal to the base metal, are usually machinable, and have an exceptionally smooth finish.

Cupro-nickel.—The materials in this group are well adapted to fusion welding. However, the following sources of trouble are encountered in their welding, and care should be taken to overcome them: (1) The refractory influxible nickel oxide causes the metal to solidify with a rough surface. (2) The metal tends to absorb gas when molten and tends to reject it when solidifying, and porosity thus is caused. (3) There is a tendency toward red-shortness. (4) There is danger of burning out the protective deoxidizers.

With metallic-arc welding, heavily flux coated electrodes should be used in order to ensure sound and strong welds. Carbon-arc welding of this material is not popular.

Aluminum Bronze.—Aluminum bronzes are materials in which the copper is alloyed with aluminum instead of tin. Up to about 10 per cent aluminum may be held in solution. These bronzes have qualities superior to those of ordinary bronze.

As a rule, these alloys are harder and more readily forgeable than the alpha brasses. They are most readily welded by means of a long carbon arc. A straight fusion weld may thus be formed, and the deposit is enhanced by a suitable flux covering. The weld should be deposited as nearly as possible in the flat position. Metallic-arc welding is not recommended.

Beryllium Copper.—Beryllium is added to copper to make the resultant metal harder and stronger. This alloy is susceptible to heat-treatment and will attain its maximum strength and hardness with a final precipitation heat. Therefore, the strength of the welded joint may be greatly improved by heat-treatment. This may be done by hot-rolling, forging, or a homogenizing anneal. The beryllium oxide film may be prevented from forming, although it will not be dissolved, by the usual brazing fluxes.

Beryllium copper is best welded by means of the carbon arc; for it is possible, with a short arc and a high heat, to have the weld metal flow into the base before the tough beryllium oxide film is formed. Although not essential, a thin application of flux is often desirable. Because of the extreme fluidity of the metal, the welding should be done only in a flat position, and a copper backing strip should be used.

GALVANIZED STEEL

Galvanized steel is a steel to which has been applied a coating of zinc in order to protect it against corrosion, especially atmospheric corrosion.

Zinc has a melting point about 786°F., and also has the property of volatilizing when heated to about 1700°F. Therefore, when galvanized iron or steel is fusion-welded, the zinc coating is heated to the melting temperature of steel, about 2750°F., and is volatilized, in the path of the weld, forming clouds of white zinc oxide. On the other hand, when bronze electrodes are used, they will melt at about 1625°F., or below the volatilization point of zinc; and when care is used, few or no clouds (fumes) result.

Zinc oxide fumes are very objectionable to the welder and often cause nausea. The welding of galvanized materials should therefore be done in well-ventilated locations whenever possible. If the welding must necessarily be done in confined spaces or if the job is of considerable duration, the operator should be supplied with a suitable respirator. Drinking plenty of milk is often recommended as an antidote for nausea.

Fusion welding of galvanized steel may be done by metallic arc. The procedure is the same as that generally used for ordinary mild steel.

Galvanized steel can be brazed with the carbon arc without injury to the galvanized coating. The filler metal used is a copper-silicon-manganese alloy, such as Everdur, Herculoy, Olympic bronze, and similar materials.

The size of the carbon electrode depends upon the thickness of the metal being brazed and the diameter of the filler rod used, but usually it ranges from 5/32 to 5/16 in. in diameter. The carbon electrode should be pointed with a gradual taper and held in the electrode holder about 1½ in.

from the point so that during operation it will keep itself necked down and tapered.

The size of the filler rod should be large enough to produce the desired width of bead without requiring much weaving motion of the carbon. The filler rod should be held down in the arc stream at an approximate angle with the plate of 10 to 20 deg.

A very short arc should be used. It should never be drawn directly from the galvanized base metal, but through and over the flowing bronze. The heat should be kept low so that the galvanizing is not disturbed.

If properly done, the carbon-arc welding of galvanized steel produces a joint of high physical characteristics and corrosion-resisting properties.

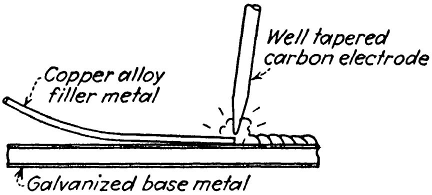


FIG. 201.—Carbon-arc welding of galvanized base metal.

One patented method of carbon-arc welding makes use of a copper-alloy tin-coated filler rod. With proper procedure, the heat zone of the weld is covered with molten tin (melting point 449°F., volatilization point 4100°F.), and thus the zinc is protected while the copper alloy rod (melting point 1868°–2264°F.) is being deposited. Added corrosion resistance is provided by the resultant coating of zinc and tin alloy along the weld.

ALUMINUM AND ALUMINUM ALLOYS

Aluminum is a silvery white metal of very low weight per unit volume, is highly corrosion resistant, has high thermal and electrical conductivity, and has low strength in its cast or annealed condition.

Aluminum and various aluminum alloys can be fusion-welded either by metallic arc or by carbon arc. The highly heated zone obtained with the arc prevents excessive expansion of the parts being welded, and thus less distortion is set up. With the arc process, the preparation of the joints for welding is simple and the rate of welding is fast.

Ordinarily, it is not practical to make butt welds on this material when it is lighter than 0.06 to 0.08 in. in thickness, owing to the relative difficulty of controlling the arc. Fillet-weld joints on material much lighter than $\frac{1}{8}$ in. in thickness are also not recommended.

For metallic-arc welding, electrodes should be of the heavily flux coated type. The electrode coating should be capable of dissolving any aluminum oxide that may be formed during the welding process. The coating should also form a very fusible slag to cover the deposited molten weld metal and thus protect it from oxidation while cooling. The proper electrode size depends upon the gauge of the material to be used, as shown in Table XIII.

The high melting rate of most aluminum electrodes necessitates a high welding speed, and it is sometimes difficult to get sufficient heat in the work. Thus, it may be necessary to preheat slightly. Lack of heat may result in porosity along the line of fusion.

Best results will be obtained when the polarity of the current is reversed, that is, when the electrode is positive and the work negative. Direct current is to be preferred to alternating current. A short arc should be held, and the electrode coating should almost touch the molten pool of metal. The electrode should be held almost perpendicular to the work at all times. The arc should be directed so that both edges of the joint to be welded are properly and uniformly heated. The rate of welding should be such as to produce a uniform bead. Before starting a new electrode, care should be taken to remove the slag from the crater of the weld and from approximately 1 in. of the weld behind the crater. In starting a new electrode, the arc should be struck in the crater of the bead, then quickly moved back along the completed weld for about ½ in.; and after the crater is completely remelted, the welding should proceed forward.

TABLE XIII.—ELECTRODE SIZE FOR WELDING ALUMINUM

Thickness of material, in.	Electrode diameter, in.	Current, amp.
0.064	⅛	45– 55
0.081	⅛	55– 65
0.102	⅛	65– 75
⅛	⅛	76– 85
5/32	⅛ or 5/32	85–100
3/16	5/32	100–125
¼	5/32 or 3/16	125–175
5/16	3/16	175–225
⅜	¼	225–300

In general, the slag may be removed by first chipping off the excess slag, then soaking the weld in hot 3 per cent nitric acid solution or warm 10 per cent solution of sulphuric acid for a short time, and finally rinsing the weld with hot water.

Vertical welding of aluminum may be done either in a downhill or in an uphill direction. In advancing the arc, either a straight-line forward motion or a weaving motion may be used. In overhead welding, a number of straight beads should be employed.

To prevent warping, often the work is positioned in jigs and backed up by copper.

High-purity Aluminum.—This alloy has a higher purity than commercially pure aluminum. It does not require any special treatment from the standpoint of welding technique, in respect to equipment, preparation of joints, or machine settings. For metallic- and carbon-arc welding, special flux-coated electrodes with a filler material of high-purity wire should be used.

Fusion welds in high-purity aluminum have comparatively high ductility. Their tensile strength is equal to the strength of the annealed temper of the parent material, regardless of the temper of the material prior to welding.

Commercially Pure Aluminum.—All the commercial forms of this material can be readily arc-welded, and commercial applications have been made on parts ranging from 0.020 to 1 in. in thickness. The welds have high ductility and excellent resistance to impact or shock loading, and their corrosion resistance is as high as that of the base metal. A tensile strength equal to that of the annealed material is obtained in the welds.

Flux-coated aluminum-silicon-alloy electrodes should be utilized in the metallic-arc welding of commercially pure aluminum. However, coated commercially pure aluminum electrodes should be used where maximum resistance to chemical attack is important.

Aluminum-Manganese Alloy.—This alloy is used wherever higher strength than can be obtained with commercially pure aluminum is required. The welding procedure is the same as for the previous material.

Aluminum-Magnesium-Chromium Alloy.—This material has considerably higher mechanical properties than the previously mentioned alloys. It is rather sensitive to the application of welding heat; and cooling cracks, caused by the shrinkage, may occur when the weld cools. However, with the metallic- or carbon-arc-welding processes, the heat is concentrated to a narrow zone and the difficulties from cracking are practically eliminated. The standard arc-welding technique with silicon aluminum electrodes is generally used for welding this alloy.

Aluminum-Magnesium-Manganese Alloy.—This material is similar, from the welding standpoint, to the preceding alloy, and the discussion above applies.

Aluminum-Silicon-Magnesium Alloys.—The alloys in this group rely on proper heat-treatment for their strength. Upon welding the heat-treating effect may be partly obliterated by the welding heat, with consequent lowering of properties.

These alloys may be advantageously welded by metallic or carbon arc, for little difficulty is experienced from cooling cracks. The strength of the weld, because of the cast structure present in the weld, is usually less than that of the base metal. Silicon aluminum electrodes of the flux-coated type should be used.

Aluminum-Copper-Magnesium-Manganese Alloys.—These alloys have their strength increased to a maximum by heat-treatment operations. They are not generally welded, for, upon welding, their mechanical strength and resistance to corrosion are reduced. However, if the service stresses are low, these materials can be arc-welded.

NICKEL AND NICKEL ALLOYS

Nickel and nickel alloys may be arc-welded by the same general procedure as mild steel.

Rolled Nickel.—In metallic-arc welding of rolled nickel, excellent welding characteristics may be obtained by using a heavily flux coated electrode of the shielded-arc type. The resultant welds have high ductility, strength, and soundness, good penetration, and no undercutting. Nickel is satisfactorily welded with reversed polarity and a short arc. The welding may be done in any position.

Nickel may also be welded by the carbon-arc process; but, in this case, straight polarity must be used, and the electrode should be of suitable type. Because of the ease of working, the carbon arc is used widely on sheets 0.062 and 0.050 in. thick.

Monel Metal.—Monel metal is an alloy consisting of approximately $\frac{2}{3}$ nickel and $\frac{1}{3}$ copper. In addition, it may contain small amounts of tin, manganese, silicon, and carbon, rarely totaling more than 2 to 4 per cent.

In general, Monel metal can be welded by all processes commonly used with steel, including metallic arc and carbon arc. The arc-welding characteristics of this metal have been improved by the development of a heavily flux coated electrode of the shielded-arc type. The thicker fluxes act as a miniature electric furnace and result in welds of great ductility, strength, soundness, and good penetration without any undercutting. The higher concentration of heat also results in higher welding speeds and thus in less warping or buckling.

For plates up to $\frac{3}{16}$ in., the diameter of the electrode should be approximately the same as the thickness of the plates being joined. For heavier plates, either a $\frac{5}{32}$- or a $\frac{3}{16}$-in. electrode can be used. In general, very satisfactory results will be obtained if the electrode is held in position ahead of the arc, and the rod is held at any angle between 45 deg. and vertical. A uniform short arc is recommended.

Monel-metal electrodes of the shielded-arc type should be used on reversed polarity.

79 Per Cent Nickel-13 Per Cent Chromium-6 Per Cent Iron Alloy.—This material may be metallic-arc welded by employing an electrode with a suitable flux coating. Reversed polarity should be used. The welds are usually ductile and strong.

Nickel-Copper-Aluminum Alloy.—This is a nonmagnetic heat-treatable alloy, and welds made upon it must have similar characteristics. Thus, it is necessary to use a coated electrode of the same alloy. Welds deposited by the metallic-arc process can be annealed or hardened by heat-treatment.

Nickel-clad Steel.—Nickel-clad steel is a ply material having a thin surface of pure nickel on a foundation of mild steel. The nickel cladding is firmly and permanently bonded to the steel base and will not separate from it because of temperature change, pressure, vacuum, or forming operations. This excellent bond between the cladding and base plate gives the clad plate a heat conductivity equal to that of solid steel or solid nickel plate. The thermal coefficients of expansion of the nickel and steel are almost identical.

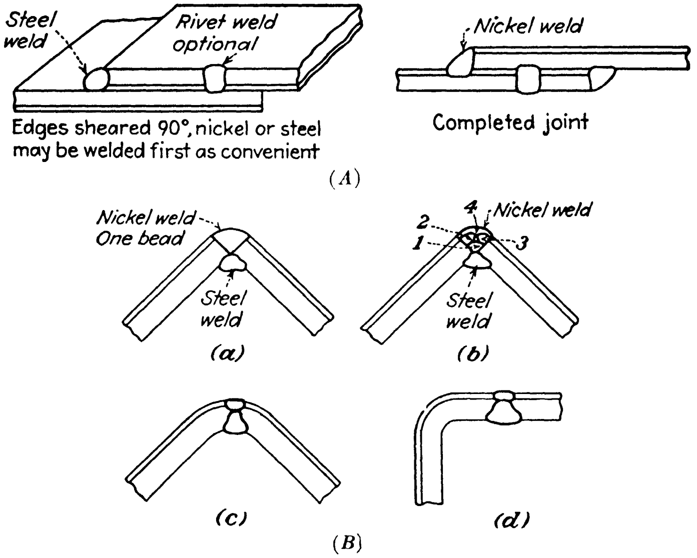


FIG. 202.—Welding of nickel-clad steel by metallic arc: (*A*) lap welds; (*B*) corner welds.

In welding nickel-clad steel, the nickel side is welded with nickel rod to obtain a continuous nickel surface which protects the steel base from corrosion at the joint. The metallic-arc process is generally used for welding heavy steel plates.

The generally recommended procedure for welding nickel-clad steel, particularly with beveled butt joints, is as follows: (1) The work to be welded should be assembled by tacking from the steel side. (2) The weld on the nickel side should be completed with a single bead. (3) The tack welds should be chipped out, and the root of the bevel cleaned. (4) The weld on the steel side should be completed with a mild-steel shielded-arc-type electrode.

However, if beveling is done by hand chipping, it is usually desirable to weld the steel side first to avoid the possibility of burning through and to prevent uneven welding and other difficulties arising from variations in the separation of the joint and the thickness of the lip at the root of the bevel.

Peening is desirable to compact the nickel weld and to increase the weld density, strength, corrosion resistance, and appearance. However, only flat-faced tools with slightly rounded corners should be used, so as to not cut into the nickel along the line of weld.

Various types of joint are used to meet construction requirements, and some of them are illustrated in Fig. 202.

DISSIMILAR METALS

Many welding operators have learned, by experimenting, how to weld dissimilar metals together, as copper to brass and steel, and Monel metal, high-speed steel, and stellite to mild steel. Various methods may be employed, and it is advisable to consult the manufacturers of metals, electrodes, and welding equipment if such problems should arise.

HARD-SURFACING

Hard-surfacing consists in welding onto wearing parts a facing, edge, or point of hard metal exceptionally resistant to abrasion. This restores or prolongs the life of parts that are subjected to an unusual amount of wear.

The hard-surfacing procedure is similar to that which applies to any steel welding. To ensure a good bond without slag inclusions, the parts to be welded should be thoroughly cleaned by chipping, grinding, or sandblasting. Preheating should be employed if weld contraction may cause cracking.

Several alloys may be used for this purpose. Although their application in the form of electrodes by the electric arc is relatively simple and easy, the operator should obtain detailed information on their application from the suppliers of welding electrodes.

CHAPTER XI

EXPANSION, CONTRACTION, AND RESIDUAL STRESSES IN WELDED STRUCTURES

The welding operator should fully understand, not only the expansion and contraction of metals, but their effects upon a welded structure as well.

TABLE XIV.—APPROXIMATE EXPANSIONS OF METALS WITH HEAT*

	500°F.		1000°F.		1500°F.	
	Expansion, in. per in.	Expansion, in. per ft.	Expansion, in. per in.	Expansion, in. per ft.	Expansion, in. per in.	Expansion, in. per ft.
Aluminum	0.006	0.074	0.012	0.148	Melts at 1218°F.	
Brass	0.005	0.057	0.010	0.115	0.014	0.172
Bronze	0.005	0.058	0.010	0.118	0.015	0.176
Copper	0.004	0.053	0.009	0.106	0.014	0.159
Iron:						
Wrought	0.003	0.039	0.006	0.078	0.010	0.117
Cast	0.004	0.045	0.007	0.090	0.011	0.135
Lead	0.007	0.090	Melts at 621°F.			
Monel	0.004	0.044	0.007	0.088	0.011	0.132
Nickel	0.003	0.042	0.007	0.085	0.011	0.127
Steel	0.003	0.038	0.006	0.076	0.010	0.116
Steel, stainless	0.004	0.056	0.010	0.112	0.014	0.168

* Expansion rates vary with temperatures. Expansions per inch and per foot are approximate averages.

In most cases, expansion and contraction produce no harmful results; but when certain conditions are present, they may bring about a reduction in strength of the weld or work, failure of the joint, or an undesirable distortion of the welded parts. However, as will be seen later, these harmful results can be reduced by employing a suitable form of weld, a proper form of joint, proper preparation, or special treatment during and after the welding operation.

Expansion and Contraction.—It is common knowledge that metals expand when heated, no matter what the source of heat, and contract when cooled. If a body of metal is heated and then held so that it cannot contract, forces, whose magnitudes are generally not realized, are set up by the cooling process.

During deposition, the weld metal is in an expanded state because of its high temperature. Upon solidifying and subsequently cooling, it tends to shrink. This shrinkage, which is volumetric or three-dimensional, unless restricted may amount to about 1 per cent. Thus, if the weld is about 10 in. long, it may shrink about 0.01 in. A force sufficient to stretch the cold bead 0.01 in. would be required to restrain the bead from shrinking. This force would by no means be small.

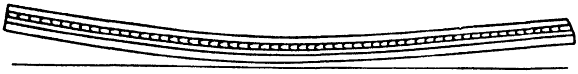


FIG. 203.—Longitudinal contraction of bead. (Steel strip left free to move while weld cooled.)

When a weld is deposited lengthwise on a light, narrow, and perfectly flat strip of metal that is not clamped or held in any way, the strip will be found to bow upward in the direction of the bead (see Fig. 203). This is due to the *longitudinal* contraction of the weld metal upon cooling.

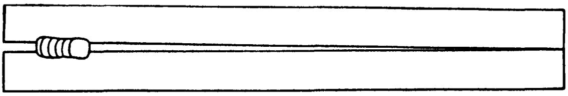


FIG. 204.—Transverse contraction of bead. (Steel strips drawn together by contracting weld metal.)

If small electrodes and low current are used in depositing the weld, little warping in the direction indicated will result, because of the relatively small amount of metal that is heated to a high temperature. Also, if the bead is deposited with large electrodes and high current, so as to produce nearly complete penetration of the strip, very little warping will again be noticed. The bottom of the strip is heated as much as the top, and therefore the shrinkage is the same on both sides of the strip. Maximum warping, then, is produced by a welding condition somewhere between these two extremes.

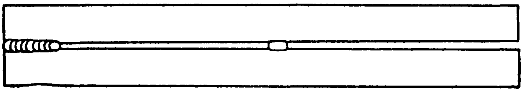


FIG. 205.—Weld started with wedge in place.

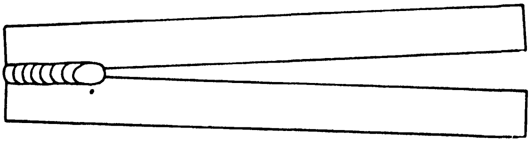


FIG. 206.—Prespacing of plates.

If two plates being butt-welded together are not too heavy or held together, and are thus free to move, they will be drawn closer together by the contraction of the weld metal (see Fig. 204). This is called *transverse* contraction. The amount of drawing, to a certain extent, depends upon the speed of welding. As a rule, the greater the speed, the less the amount. A speed at which the plates will not draw together can be found. The drawing together may also be satisfactorily prevented by keeping a wedge between the plates, 12 to 18 in. ahead of the welding (see Fig. 205). Another good way, if possible, is to separate the plates to make allowance for the contraction (see Fig. 206). A spacing of approximately ⅛ in. per lin. ft. of weld is found to be satisfactory for usual thicknesses. However, the exact amount varies with different jobs and conditions.

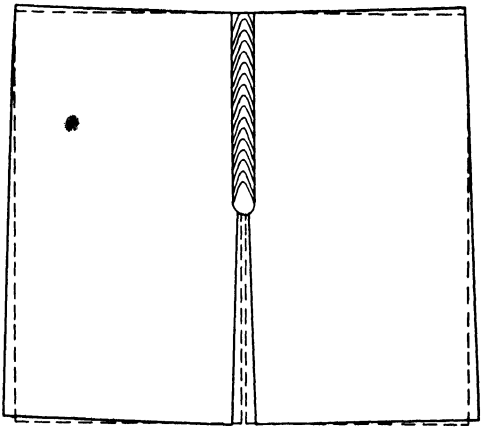


Fig. 207.—Dotted lines show original position of plates. Solid lines indicate plates after welding at high speed.

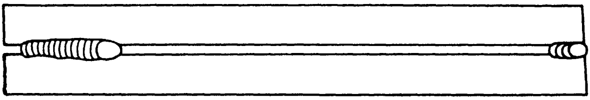


Fig. 208.—Method of "tacking" ahead of weld.

In using heavily coated electrodes, the plates may separate while welding proceeds because of the high speed of welding involved (see Fig. 207). To overcome this, the ends of the plates should be clamped down or tacked together before beginning to weld (see Fig. 208).

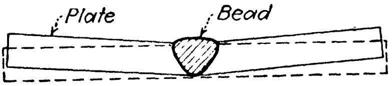


Fig. 209.—Original position of plates is indicated by dotted lines. Position after welding is shown by solid lines.

In welding the beveled edges of thick plates, such as in making a single-Vee butt weld, it will be frequently found that the plates are pulled out of line with each other (see Fig. 209). The opening at the top of the vee being greater than at the bottom, a greater portion of the metal is deposited there, and therefore the drawing is greatest on that side of the joint.

If two plates are welded at right angles with a bead on one side only, it will be found that when the weld has cooled the plates are no longer at right angles but the weld has pulled the pieces toward each other in the direction of the weld (see Fig. 210).

Residual Stresses.—It has been seen that when a bead of weld metal is deposited longitudinally upon a flat steel strip the weld metal, upon cooling, tends to contract and this action bends the steel strip into a bow. By taking such a shape, some of the contractive stresses in the weld metal are partly relieved, but sufficient stresses are still present to bend the steel strip. To prove this, it will be found that if the entire bead is cut off the strip will spring back to a flat shape. If the strip has been bent or bowed enough to cause a permanent set, it will not quite resume its original flat shape, but it will spring back enough to assume a flatter shape than it had before the bead was removed.

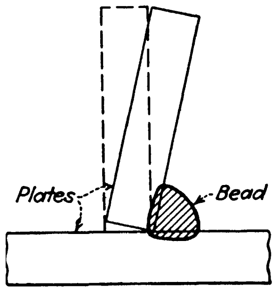


FIG. 210.—Dotted lines indicate position before welding. Solid lines indicate position after welding.

The above-mentioned stresses are called *residual*, or *locked-up*, *stresses*. Several factors determine the amount of harm done by these stresses. Where the work and the deposited weld metal are both ductile, the flow of the metal will partly relieve the stresses. Examples of such ductile materials are mild steel and wrought iron; and, in most instances, welds made upon them do not require any elaborate precautions to avoid locked-up stresses.

Residual stresses are low if the weld is made on thin material and the parts are permitted to bend, but they are high in materials with little ductility or in structures of great rigidity, such as large castings.

Residual stresses are not of serious importance where the welded members are subject to very gradually applied load stresses or to steady stresses. However, residual stresses may become serious where loads are suddenly applied. In such cases, stress relieving is not only desirable, but necessary.

Control of Residual Stresses.—The following precautions should be taken to prevent the failure of a weld due to residual stresses:

1. The product should be designed, as far as possible, so as to incorporate types of joint having the lowest residual stresses.

2. The assembly and welding sequences should permit the movement of the component parts during welding; they should keep joint fixity to a

minimum; and the joint of maximum fixity should be welded first. To illustrate, the longitudinal seam of a cylindrical tank should be welded before the circumferential head seams.

3. All layers, except root and face, of multiple-layer welds of appreciable fixity should be peened. At the same time, for effective peening, they should not be more than ⅛ in. in thickness.

4. Highly localized and intersecting areas should be avoided.

5. An intermittent sequence of welding should be used, such as "skip," "wandering," or "step-back" welding. This would prevent the accumulation of stress by keeping the expanding zones sufficiently narrow and sufficiently close to the contracting zones so that they tend to stress relieve or neutralize each other (see Fig. 211).

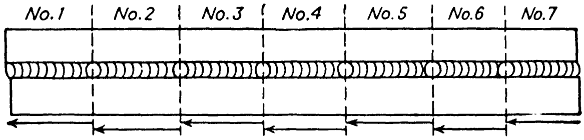


FIG. 211.— A typical "step-back" weld.

6. The welds should have shapes, sizes, and continuities capable of resisting the service and anticipated residual stresses. For instance, butt welds should be of the continuous type and should have throats at least equal to the thinner section joined.

7. In respect to methods of assembly and the sequence of welding the introduction of bending stresses in the weld should be avoided.

8. To prevent the possibility of a failure of the weld ends and a subsequent progressive failure of the joint, the welds on the ends of members should be "boxed," or welded around the end.

9. All cracked tack welds and all defective sections of strength welds should be chipped or melted out before proceeding with the work. Cracks are great stress raisers.

10. Unless properly authorized, the practice of using metal slugs in the weld to speed up production or to fill in badly fitted grooves should not be permitted.

11. The operator should be capable of making welds that are free from defects and whose physical properties comply with the minimum process qualification requirements. He should not be permitted to make welds in positions for which he is not qualified, or poor welds will result.

Stress Relieving.—A stress will be relieved if plastic flow or deformation is developed in the stressed section. This flow or deformation may be secured by employing such methods as heating, annealing, peening, or stressing the metal behind the yield point.

Heat-treatment is the most common method of stress relieving. For a satisfactory treatment, the heating should be done in a furnace capable of uniform heating, under temperature control. A method of heating not injurious to the metal being treated should, of course, be used. To avoid distortion of the members, some sort of support should be provided. The rise in temperature should be gradual. All parts should be heated throughout their thickness at a uniform rate.

Mild steel requires a maximum, or soaking, temperature ranging from 1100 to 1200°F. The temperatures required by other steels are somewhat higher, depending upon the reduction in yield point and the yield characteristics of the material. Some alloys require a soaking temperature of 1600°F. or above. The thickness of the parts and the plasticizing rate of the metal of which they are made determine the length of time the member should be held at this maximum temperature. A soaking period of 1 hr. per in. of thickness of material is commonly used for structures of mild steel having uniform thickness or uniform degree of restraint, such as pressure vessels. If a structure is made up of parts having widely different thicknesses, the structure should be heated long enough to ensure stress relieving in the thickest parts. To prevent serious distortion of the lighter parts, the latter must be adequately supported.

The temperature must be gradually reduced at a rate ensuring approximately uniform temperature throughout all parts. This operation requires as much as 48 hr. for structures of widely varied thicknesses. The process is much more rapid for structures of uniform thickness.

A number of conditions dictate the temperature at which the structure should be withdrawn from the heating chamber. To prevent new residual stresses, it is essential that structures having members of variable rigidity be reduced uniformly to the atmospheric or ambient temperature. A still air is very desirable after the furnace is opened and until the structure is fully cooled.

If total heating of the structure is not possible because of its size, as in the case of pipe lines, it may be possible to stress-relieve by heating only a portion of the structure at a time. This should be carefully done so that the end of the heated zone lies in a flexible part of the structure. Unless the affected part may expand and contract with comparative freedom, stress relieving by local heating should not be undertaken, or restressing may occur to an extent perhaps equivalent to the original residual stress.

Preheating the parts to be welded is desirable in certain instances, so that, upon cooling, the stresses that would otherwise accumulate are prevented. Residual stresses may be produced by overheating and underheating; therefore, preheating should be carefully planned and controlled.

Welded parts may be *fully annealed.* This method is superior to other types of stress-relieving but cannot be indiscriminately used because of the heavy scale produced with some metals at the high temperatures required (1600 to 1650°F. for mild steel). Also, some types of product would collapse at these temperatures.

Peening has been employed with success for stress-relieving purposes. When properly applied, it causes plastic flow and subsequently relieves the restraint that set up the residual stresses. Effective peening, however, requires considerable judgment. Excessive peening may result in the cold-working and strain-hardening of the material; and, what is more, it may set up new residual stresses. Peening by hand is generally not satisfactory, for it cannot be properly controlled. A pneumatic chisel with a blunt rounded edge is generally used.

Peening of a stressed region is usually done at a temperature cool enough to permit the hand to be placed on it without serious discomfort. But at times it is found necessary to peen immediately after depositing the weld and, in other cases, after the weld has cooled to room temperature. As far as the final value of the residual stress is concerned, it makes no difference which method is used.

A residual stress may also be relieved by *stressing* the welded structure *beyond the yield point.* This may be done by mechanical, hydrostatic, or other suitable means. With pressure vessels, it is not uncommon to apply internal pressure and to increase the latter until the metal has reached the yield-point stress throughout. When such pressures are removed, the residual stresses will be found to have largely disappeared. As in peening, to prevent strain-hardening or embrittling the steel, only a very small yielding should take place. Also, all parts of the vessel should reach the yield point at the same time, or other residual stresses will be introduced.

The method of stressing the parent metal beyond the yield point is rarely used because of the problems involved in its practical applications.

Control of Shrinkage.—In nonpreheated products, the shrinkage due to welding may be controlled or reduced to a minimum by employing (1) closed roots of joints, (2) the minimum number of welds, (3) the smallest size of welds that fulfills the requirements of design, fabrication, and service, (4) the minimum number of layers required to satisfy the wanted weld properties, (5) the maximum use of intermittent welds, and (6) the peening of welds in the cold state, except root and face layers.

Control of Warping.—The methods outlined for the reduction of shrinkage will be found very helpful in wholly or partly eliminating the warping in nonpreheated welded structures. However, other means of control may also be employed.

To prevent warping during welding, fixtures holding parts in place may be used; or, before making strength welds, the product may be partly or completely assembled by tack welds, to allow the assembled product to function as its own welding fixture.

If jigs or fixtures are not available, the parts to be welded should be deformed in the reverse direction to that in which warping would occur under normal conditions. This deforming may be done mechanically or by application of heat. The method works out to a great degree of accuracy on repetitive work.

The type of joints and welds used should permit the application of weld sequences that tend progressively to balance each other. To illustrate, the double-Vee butt joint should be used instead of the single-Vee. Also, on heavy welds, the welding of seams symmetrically disposed with respect to the center of gravity of the weld itself should be simultaneously done by two or more operators.

CHAPTER XII

WELDING JIGS

A *welding jig* is any device capable of holding in established relationship the parts to be welded into an assembly. A *welding fixture* serves the same purpose as a welding jig; but, in addition, it permits the changing of the position of the work during the actual welding, so as to place the welds in a plane convenient to the operator at all times. But since it is rather difficult to distinguish between jigs and fixtures, it is customary to refer to any work-holding device for welding purposes as a welding jig.

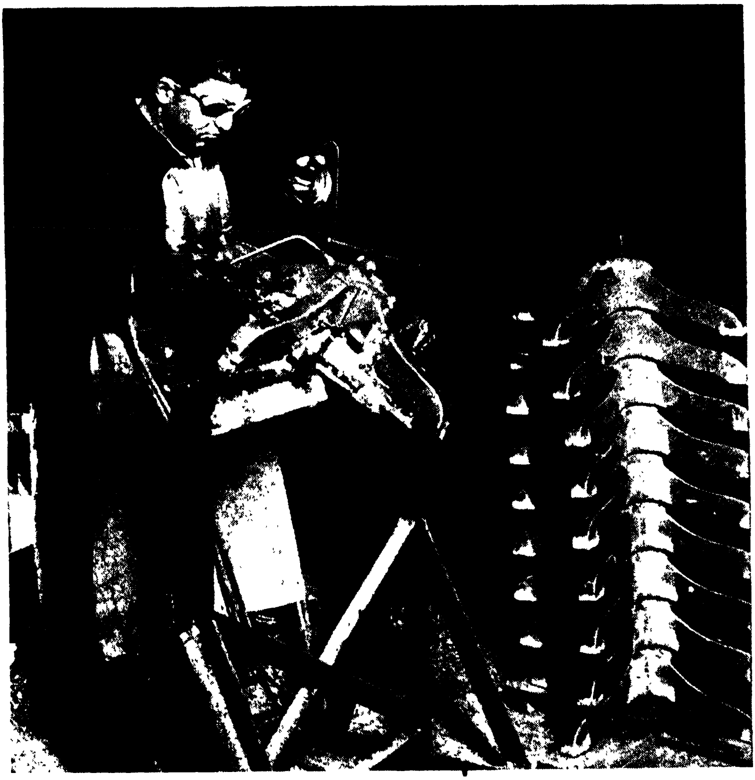


Fig. 212.—Typical production welding jig. (The parts to be joined are carefully located in the required position. The jig is so designed that it does not permit any piece to be assembled out of place.) (*Courtesy of The Linde Air Products Company.*)

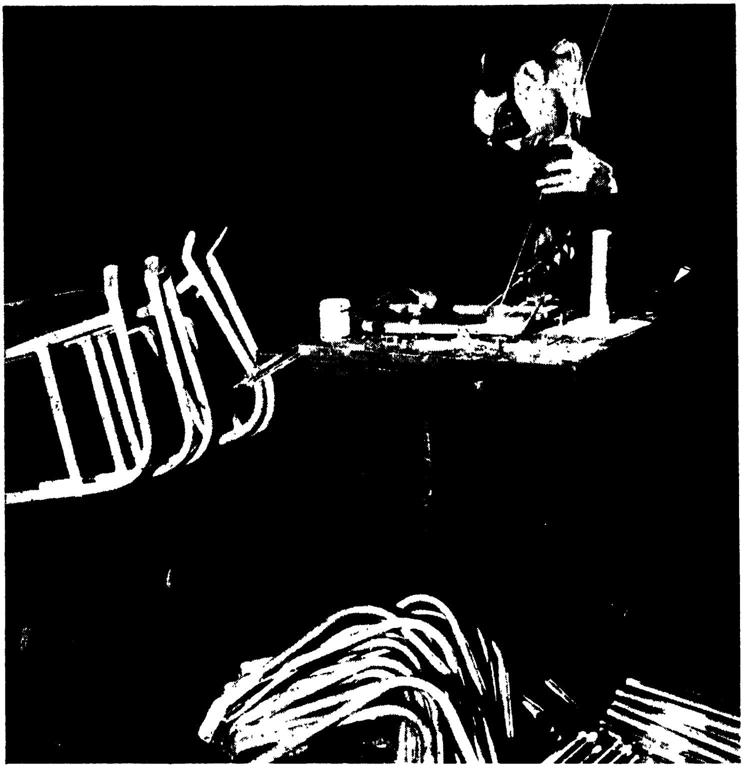
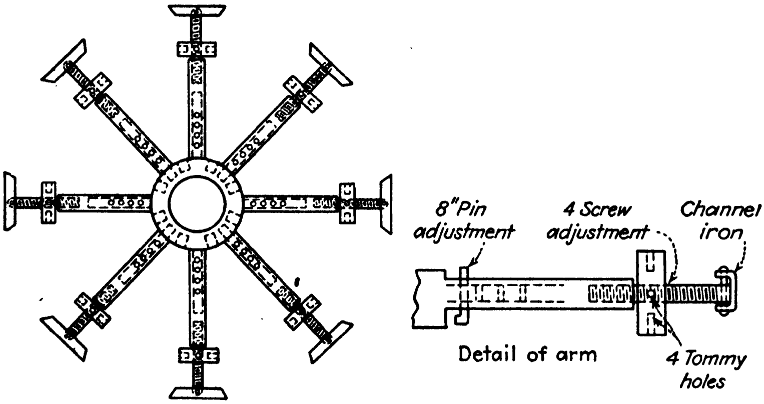


FIG. 213.—Simple jig designed primarily so that the work cannot be inserted out of position. (*Courtesy of The Linde Air Products Company.*)



Detail of arm

FIG. 214.—Flexible jig designed for holding cylindrical or octagonal tanks from the inside. (*Courtesy of International Acetylene Association.*)

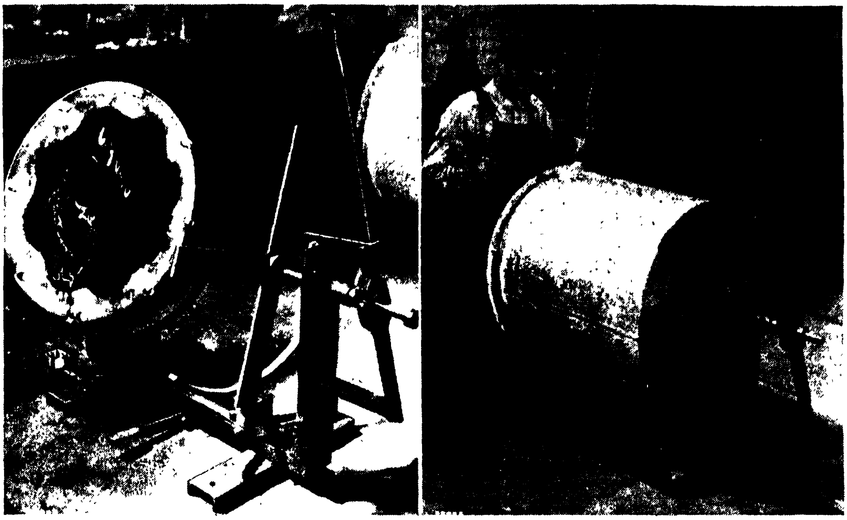


FIG. 215.—Jig for the fabrication of round galvanized containers. (*Courtesy of International Acetylene Association.*)

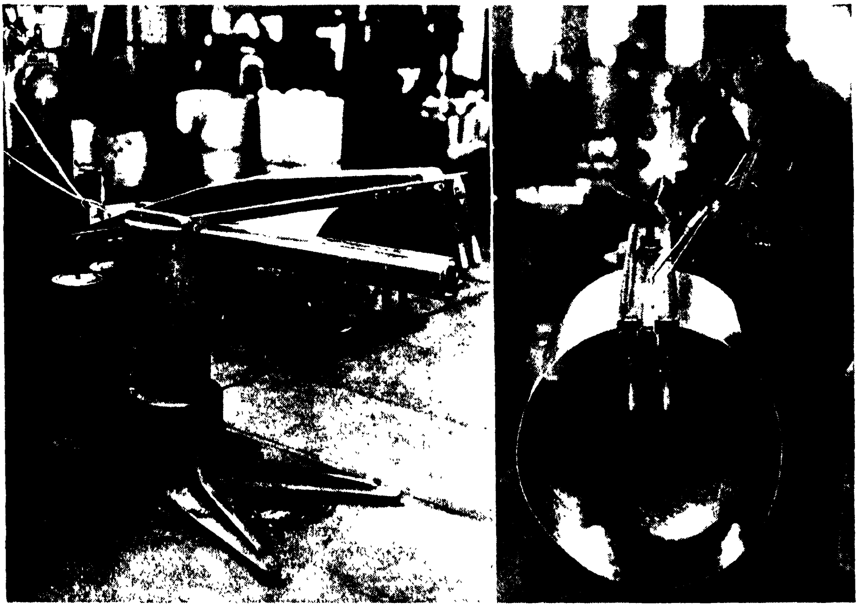


FIG. 216.—Jig for the fabrication of round tanks and containers. (*Courtesy of International Acetylene Association.*)

In addition to locating the component parts of the structure to be welded in the required position and relation, thus ensuring uniformity of size and shape, welding jigs are also used to eliminate or control the distortion of these parts during welding. Owing to the relatively greater heat effect which tends to distort the metal more as the cross section is reduced, welding jigs are needed more for metals of ⁹⁄₆₄ in. thickness and lighter than for heavier plate metals.

Fig. 217.—Jig used for the hardfacing of coal cutter bits. (*Courtesy of The Linde Air Products Company.*)

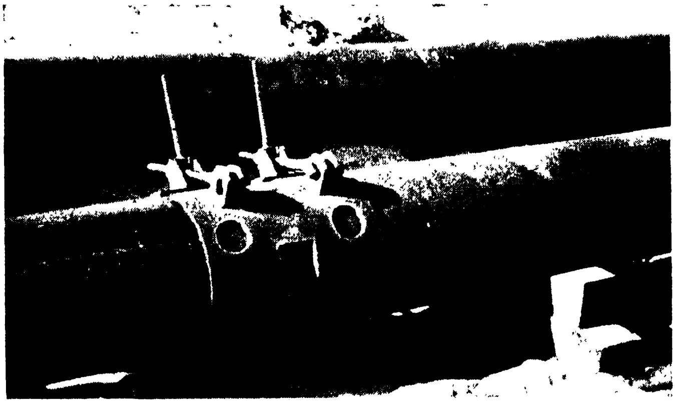


Fig. 218.—Typical jig for the alignment and tack welding of pipe sections. (*Courtesy of International Acetylene Association.*)

Designing of Jigs.—In designing a jig for any given operation, several factors should be kept in mind. The jig should bring about a saving in the final cost of the welded item. Also, it should work easily, smoothly, and rapidly; it should be made light and portable; it should not constitute a safety hazard for the operator; and it should be so designed that the work can be inserted only in the correct position (see Fig. 213).

The locating points of a jig should be very visible to the operator; and, if possible, they should be adjustable so as to make the use of the jig very flexible (see Fig. 214). If any clamps are used, they should operate rapidly and smoothly. To prevent their becoming overheated, they should not be exposed to the welding heat.

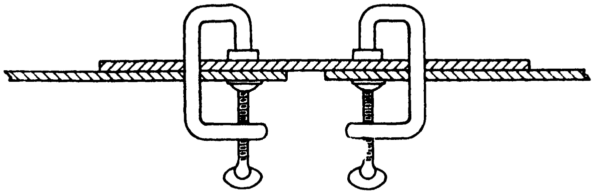


Fig. 219.—C clamps.

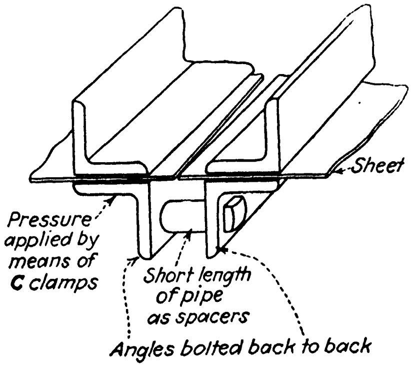

Sheet
Pressure applied by means of C clamps
Short length of pipe as spacers
Angles bolted back to back

Fig. 220.—Angle-iron bars.

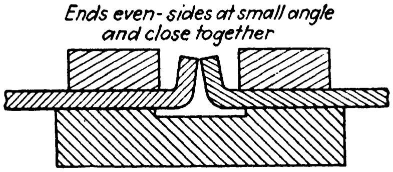


Fig. 221.—Rectangular bars.

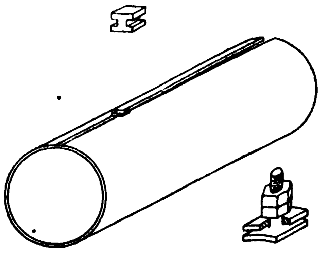


Fig. 222.—Spacers.

It is also important to make allowances for the control of heat both in the jig and the work.

Various Forms of Jigs.—Various forms of jigs are illustrated in Figs. 212 to 218.

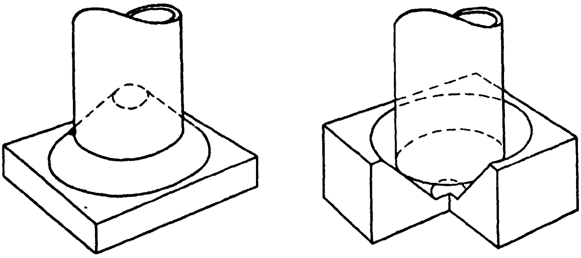


FIG. 223.—Cup-and-cone devices for locating concentric cylindrical parts of work

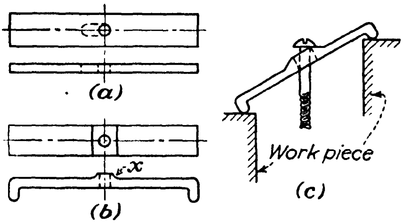


FIG. 224.—Straps.

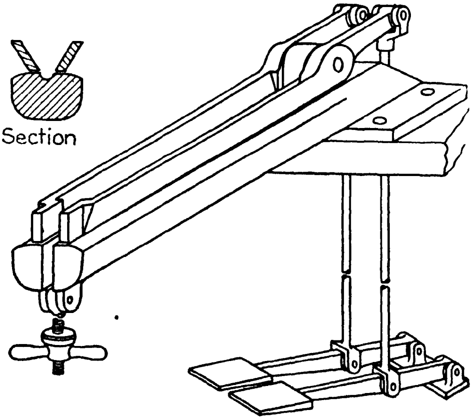


FIG. 225.—Swinging leaves. (Utilizing a screw type of clamping device.)

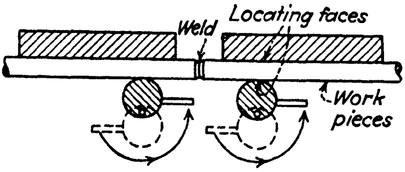


FIG. 226.—Cam and lever.

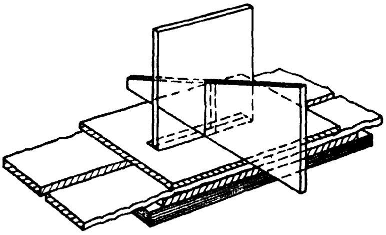


FIG. 227.—Wedge.

There are a large number of miscellaneous holding devices that, though strictly speaking they cannot be called jigs, should at the same time be taken into consideration because they form the most elementary type of work-holding devices. Among them are C clamps, angle irons, heavy bars, Vee blocks, simple levers, and simple wedges (see Figs. 219 to 222).

Since their application requires hand adjustment and thus takes time, they are not satisfactory for production work. Rather, they are best suited for those jobs which occur only occasionally and which do not justify the fabrication of a better jig.

Locating Points and Clamping Devices.—The accuracy of the finished work depends to a great extent upon the locating points and clamping devices.

The locating points may consist of pads, bosses, lugs, pins, studs, cup-and-cone arrangements (see Fig. 223), stationary or movable screws, and finished holes, corners, and edges.

The kind and number of locating points to be used in a specific jig should be accurately determined in accordance with the nature of the work.

The clamping devices should have simplicity and positiveness of action and should need a minimum of adjustment. Among the main types of clamping devices are straps, leaves, wedges, and eccentrics (see Figs. 224 to 227).

CHAPTER XIII

METALLURGY OF WELDING

Broadly speaking, metallurgy is the art which embraces all phases of working with metals as raw materials, including their production and preparation, up to the point of fabrication or manufacture with the fully prepared material. That part of metallurgy which deals with the change in properties of metals as they are heated is, without any doubt, the branch of engineering most closely related to the welding process.

SOME GENERAL PRINCIPLES OF METALLURGY

To understand the metallurgy of welds, it is necessary to become acquainted with some of the fundamentals of metallurgy in general.

Definition of Metals and Alloys.—Chemical elements are divided into metals and nonmetals. Of the 92 known elements, about 70 are metals, and of these about 40 are used commercially. Those chemical elements which possess metallic luster and which in electrolysis carry a positive charge and are thus liberated at the cathode are known as *metals;* those which do not possess metallic luster and which in electrolysis carry a negative charge and are thus liberated at the anode are known as *nonmetals.* Those chemical elements which have the physical characteristics of a metal but which behave chemically as both nonmetals and metals are referred to as *metalloids.*

In general, metals have high conductivity for electricity and heat. The majority of them possess high density, strength, malleability, and ductility to a much greater degree than most nonmetals.

Some of the metals that are used most widely in industry and that are therefore known as common engineering metals are: aluminum, chromium, copper, iron (steel), lead, magnesium, nickel, tin, tungsten, and zinc.

An *alloy* is a mixture with metallic properties composed of two or more elements of which at least one is a metal. For instance, iron and carbon unite to form the alloy called "steel."

Physical and Mechanical Properties of Metals and Alloys.—The properties of metallic substances may be divided into two groups: (1) those general physical properties which would be investigated in a physics laboratory, such as fusibility, magnetism, and specific gravity; (2) those properties known as "mechanical" properties, such as strength, machinability, toughness, resistance to wear, and so on. For industrial applications the mechanical properties are often considered to be more important than physical properties.

Strength.—The *strength* of a substance is its resistance to an applied strain. The *ultimate strength* is its resistance to breaking, often spoken of as failure, rupture, or fracture. The *fracture* of a metal is the surface across which the break has occurred, and its appearance often gives information on the strength and ductility of the substance.

TABLE XV.—SOME MECHANICAL PROPERTIES OF COMMON METALS AND ALLOYS

Metal or alloy	Composition	Tensile strength, lb. per sq. in.		Elongation in 2 in., per cent
		Ultimate	Elastic limit	
Aluminum (cast)	Al	12,500	8,000	20
Antimony	Sb	1,000		
Bismuth	Bi	3,000		
Brass—70-30	Cu + Zn	54,000	45,000	16
Bronze—90-10	Cu + Sn	34,000	26,000	8
Bronze-manganese	Cu + Zn + Mn	56,000	32,000	11
Cobalt	Co	37,000	30,000	1
Copper—soft	Cu	33,000	8,000	50
Duralumin	Al + Cu + Mg + Mn	61,000	36,500	19
Iron	Fe	45,000	22,000	50
Lead	Pb	3,000	Negligible	406
Magnesium	Mg	25,000	2,500	8
Magnesium-aluminum alloy	Mg + Al	42,000	37,200	8
Molybdenum	Mo	150,000		5
Monel metal	Ni + Cu	90,000	51,000	42
Nickel	Ni	75,000	25,000	45
Steel:				
Structural	Fe + C	60,000	35,000	25
High-carbon	Fe + C	125,000	75,000	10
Alloy	Fe + C + Ni + Cr + V	240,000	220,000	12
Stellite	Co + Cr + W	116,500	50,000	3
Tin	Sn	5,500		43 (?)
Tungsten (wire)	W	230,000		3
Zinc	Zn	22,000	Low	40

Tungsten wire, used for filaments of incandescent electric lights, is the strongest substance known to man. Following in order of strength among commercially pure metals are molybdenum and nickel. Of course, steel, because of its cheapness, is used more than any other metal in engineering for tensile purposes. The strengths of several other common metals and alloys are given in Tables XV and XVI.

Elasticity.—Elasticity may be defined as the power that a body possesses of resuming its original form after removal of the force that has produced a change in that form. In tension, elasticity is measured by resistance to stretching without permanent deformation. This particular factor of strength is called the *modulus of elasticity,* which is defined as the unit stress divided by the resulting unit deformation. That is, the modulus of elasticity expresses the stiffness of a body.

TABLE XVI.—AVERAGE VALUES FOR STRENGTH, STIFFNESS, AND DUCTILITY OF IRON AND STEEL

Material	Strength in tension, lb. per sq. in. (ultimate)	Strength in compression, lb. per sq. in. (ultimate)	Strength in shear, lb. per sq. in. (ultimate)	Modulus of elasticity, lb. per sq. in.		Elongation in 2 in., per cent
				Tension	Shear	
Gray cast iron	20,000	75,000	....	15,000,000	6,000,000	Slight
Commercial wrought iron	50,000	30,000	35,000	27,000,000	10,000,000	35.0
Steel:						
0.20 per cent C, rolled	60,000	35,000	45,000	30,000,000	12,000,000	35.0
Castings	60,000	30,000	45,000	30,000,000	12,000,000	30 0
0.40 per cent C, rolled	90,000	50,000	65,000	30,000,000	12,000,000	20.0
Castings	80,000	40,000	60,000	30,000,000	12,000,000	15.0
0.60 per cent C, rolled	115,000	60,000	85,000	30,000,000	12,000,000	14.0
0.80 per cent C, rolled	135,000	70,000	100,000	30,000,000	12,000,000	10.0
1.00C, annealed, rolled	150,000	80,000	115,000	30,000,000	12,000,000	5.0
0.20 per cent C, cold-rolled	80,000	60,000	60,000	30,000,000	12,000,000	18.0
Silicomanganese steel, 1.96Si, 0.70Mn:						
Annealed rolled metal	77,000	60,000	55,000	30,000,000	12,000,000	16 0
Heat-treated rolled metal	174,000	130,000	120,000	30,000,000	12,000,000	14.0
Structural nickel steel, 3.5 per cent Ni	90,000	50,000	65,000	30,000,000	12,000,000	25.0
Chrome-nickel steel, 0.40C, 1.5Ni, 1.2Cr:						
As rolled	95,000	75,000	70,000	30,000,000	12,000,000	25.0
Heat-treated	145,000	115,000	105,000	30,000,000	12,000,000	15.0
Chrome-vanadium steel, 0.40C, 1.00Cr, 0.17V:						
As rolled	85,000	45,000	65,000	30,000,000	12,000,000	28.0
Heat-treated	220,000	....	....	30,000,000	....	14.0

The *limit of elasticity* is the maximum unit stress that a body can endure without permanent deformation.

Toughness.—The resistance of metals to fracture after permanent deformation has begun is known as *toughness.* Toughness may be referred to as the opposite of brittleness; but this is true only in the sense that a tough metal gives warning of a failure before it is strained to the ultimate, whereas an extremely brittle metal fails suddenly without any warning whatever. Although there is no true measure of toughness, the commonest measure of the toughness of a metallic body is resistance to blow or impact. The relative order of the common metals with respect to their toughness is indicated in Table XVII.

Ductility.—Ductility is the ability to be permanently deformed by tension without rupture. For instance, high ductility permits wire to be drawn from a larger to a smaller size. Obviously, this involves an elongation and a reduction of area. It must be noted that ductility is the quality of being deformed by tension without rupture, whereas toughness is resistance to deformation. Table XVIII gives the order of metals with respect to their ductility.

TABLE XVII.—RELATIVE ORDER OF SOME COMMON METALS AND ALLOYS WITH RESPECT TO VARIOUS PHYSICAL PROPERTIES

Ultimate tensile strength	Elastic limit	Modulus of elasticity	Toughness
Tungsten (wire)	Tungsten (wire)	Tungsten (wire)	Copper
Molybdenum (wire)	Molybdenum (wire)	Nickel steel	Nickel
Stellite	Steel	Iron	Iron
Steel	Monel metal	Monel metal	Magnesium
Monel metal	Stellite	Copper	Zinc
Nickel	Brass	Zinc	Aluminum
Manganese bronze	Cobalt	Brass	Lead
Iron	Bronze	Bronze	Tin
Brass	Nickel	Antimony	Cobalt
Bronze	Iron	Aluminum	Bismuth
Cobalt	Copper	Magnesium	Antimony
Copper	Aluminum	Tin	
Magnesium	Magnesium	Bismuth	
Zinc	Zinc	Lead	
Aluminum	Lead		
Tin			
Bismuth			
Lead			
Antimony			

Malleability.—Malleability is the ability to be permanently deformed by compression without rupture or to be rolled or hammered into thin sheets. Malleability is similar to but not the same as ductility, and metals do not possess the two properties in the same degree, as shown in Table XVIII. For example, the strength of iron and nickel gives them a relatively higher ductility, because they will not break with the tension necessary to produce deformation. Lead and tin are more malleable, but they lack the necessary ductility to be drawn into fine wire.

Brittleness.—The suddenness of failure, or the property of breaking without visible permanent deformation, is called *brittleness.* It is the opposite of toughness.

Weldability.—*Weldability* is the capacity of a metallic substance to form a strong bond of adherence under pressure or when solidifying from a liquid state.

Resistance to Heat and Rusting.—Metals gain ductility and lose strength when heated to high temperatures. Heat also causes oxidation and scaling, except in the case of only a few metals such as gold, platinum, and chromium.

Steel rusts at atmospheric temperature; other metals discolor, corrode, or stain; others form a coating so thin as to be almost invisible. Some metals, such as chromium, nickel, zinc, and tin, are noncorroding and are used for protective coatings on other metals.

TABLE XVIII.—RELATIVE ORDER OF SOME COMMON METALS AND ALLOYS WITH RESPECT TO VARIOUS PHYSICAL PROPERTIES

Ductility	Malleability	Softness	Brittleness
(Gold)	(Gold)	Lead	White cast iron
(Silver)	(Silver)	Tin	Gray cast iron
(Platinum)	Copper	Aluminum	Hardened steel
Iron	Aluminum	Magnesium	Stellite
Nickel	Tin	Zinc	Bismuth
Copper	(Platinum)	Copper	Magnesium
Aluminum	Lead	Iron	Bronze
Tungsten	Iron	Brass	Aluminum
Zinc	Nickel	Bronze	Brass
Tin	Zinc	Nickel	Structural steel
Lead	Cobalt	Cobalt	Zinc
Cobalt	Antimony	Mild steel	Monel metal
Antimony	Tungsten	Soft cast iron	Tin
Bismuth	Bismuth	Rail steel	Nickel
		White cast iron	Copper
		Hardened steel	Iron
		Stellite	Lead

Fatigue Failure.—Metals will ultimately rupture and fail if they are subjected to frequent repetitions of a stress, even though this stress may not be sufficient to produce permanent deformation if applied continuously. Such a stress is found in the shank of a rock drill. Alternations of stress, or alternate tension and compression, will cause failure even more rapidly than repetition of stress. Failure of metals and alloys under repeated or alternating stresses is called *fatigue failure.*

Resilience.—*Resilience* is the energy stored in a material under strain within its elastic limits that causes it to resume its original shape when external strain is removed. It is commonly known as "springiness."

Hardness.—The ability of one substance forcibly to penetrate another substance without fracture of either is known as *hardness.* It is the reverse of softness. It is not to be confused with the property of brittleness, lack of ductility, lack of toughness, or of resisting wear or abrasion.

Fusibility.—Fusibility is the ease with which a substance may be melted. In general, soft metals are easily fusible, whereas harder metals melt at higher temperatures (see Table XIX).

TABLE XIX.—SOME PHYSICAL PROPERTIES OF METALS
(Arranged in order of fusibility)

Metal	Melting point		Boiling point		Specific gravity	Electric conductivity, per cent	Heat conductivity, per cent	Magnetism
	°C.	°F.	°C.	°F.				
Mercury	− 39	−38	357	674	13.6	1.7	1.8	
Tin	232	449	2,260	4,100	7.3	11.3	15.2	
Bismuth	271	520	1,450	2,642	9.8	1.1	1.8	
Cadmium	321	610	766	1,404	8.7	21.2		
Lead	327	621	1,620	2,948	11.3	7.6	8.2	
Zinc	419	787	905	1,661	7.2	26.0	28.1	
Antimony	630	1,167	1,380	2,516	6.6	3.5	4.2	
Magnesium	651	1,204	1,097	2,007	1.7	35.8	37.6	
Aluminum	660	1,220	1,800	3,272	2.7	53.0	48.0	
Copper	1,083	1,981	2,350	4,259	8.9	94.0	89.0	
Manganese	1,260	2,273	1,900	3,452	7.2			
Nickel	1,455	2,651	2,900	5,252	8.9	11.8	14.0	29
Cobalt	1,480	2,696	3,000	5,432	8.7	16.3	....	44
Iron	1,535	2,795	3,000	5,432	7.9	17.7	18.0	100
Chromium	1,920	3,490	2,200	3,992	6.9			
Vanadium	1,710	3,110	3,000	5,432	5.6			
Molybdenum	2,620	4,748	3,700	6,692	10.2	33.2		
Tungsten	3,370	6,100	5,900	10,652	19.0	28.9		

Volatility.—The ease with which substances may be vaporized is called *volatility.* As a rule, metals of low melting point are volatilized more easily than those of high melting point. Volatility is measured by the temperature at which the metal boils under atmospheric pressure.

Electrical Conductivity.—The *electrical conductivity* of a substance is the electrical conducting power of a unit length per unit of cross-sectional area.

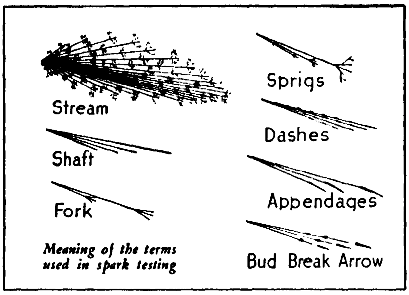
Thermal Conductivity.—Thermal conductivity is the heat-conducting power of a substance. It may be more accurately defined as the quantity of heat (B.t.u.) that flows in a unit of time (1 hr.) through unit area of plate (1 sq. ft.) of unit thickness (1 ft.) having unit difference of temperature (1°F.).

Magnetism.—Magnetism is the magnetic force exerted by a unit volume of a substance under a standard magnetizing force. Though iron is the only commercial magnetic metal, cobalt and nickel have sufficient magnetic powers to be observed.

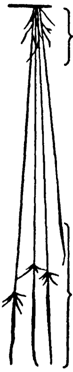
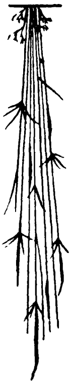
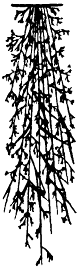
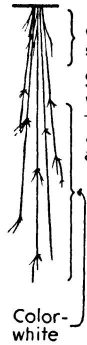
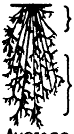
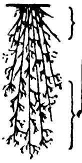
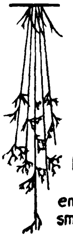
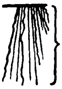
Identifying Metals by Spark Testing

Spark tests should be made on a high speed power grinder, and the specimen should be held so that the sparks will be given off horizontally. For most accurate results, the sparks should be examined against a dark background, preferably in a dark corner of the shop.

The color, shape, average length, and activity of the sparks are details which are characteristics of the material tested. Spark testing can be a very accurate method of identifying metals but it requires considerable practice and experience to become an expert. Several common sparks are given in the table. If the operator learns the technique for identifying these metals readily, he will soon be able to expand his experience to include others by observation and comparison with the sparks from known samples.



Meaning of the terms used in spark testing

Wrought Iron	Low-Carbon Steel*	High-Carbon Steel	Alloy Steel**
 Color - straw yellow Average stream length with power grinder-65 in. Volume-large Long shafts ending in forks and arrowlike appendages Color-white	 Color-white Average length of stream with power grinder-70 in. Volume - moderately large Shafts shorter than wrought iron and in forks and appendages Forks become more numerous and sprigs appear as carbon content increases	 Color-white Average stream length with power grinder-55 in. Volume - large Numerous small and repeating sprigs	 Color - straw yellow Stream length varies with type and amount of alloy content Shafts may end in forks, buds or arrows, frequently with break between shaft and arrow. Few, if any, sprigs Color-white
White Cast Iron	**Gray Cast Iron**	**Malleable Iron**	**Nickel*****
 Color-red Color - straw yellow Average stream length with power grinder-20 in. Volume-very small Sprigs-finer than gray iron, small and repeating	 Color-red Color - straw yellow Average stream length with power grinder-25 in Volume-small Many sprigs, small and repeating	 Color - straw yellow Average stream length with power grinder-30 in Volume-moderate Longer shafts than gray iron ending in numerous small, repeating sprigs	 Color - orange Average stream length with power grinder-10 in. Short shafts with no forks or sprigs

*These data apply also to cast steel

**Spark shown is for stainless steel

***Monel metal spark is very similar to nickel

FIG. 228.—Identifying metals by spark testing. (*Courtesy of The Linde Air Products Company.*)

Denseness.—Compactness, or lack of porosity, is known as *denseness.* This is not to be confused with density which denotes the weight per unit of volume. Some heavy metals, like gray cast iron, are porous enough to leak under heavy hydraulic pressures, whereas some lightweight metals, like aluminum, are dense and compact.

Porosity.—Porosity is the opposite of denseness. A porous material contains pores or voids.

Recognizing Metals.—Since welding procedure varies with the different metals, one should be able to recognize commercial metals and alloys in order to apply the proper welding methods.

A number of simple tests will aid to identify metals.

1. *Appearance test:* The color, surface characteristics, and appearance of a fractured surface are observed.
2. *Chip test:* A narrow groove is chipped with cold chisel and hammer, and the ease of chipping and the characteristics of the chips formed are observed.
3. *Spark test:* A piece of the metal is held against a power grinding wheel, preferably in a dark place, and the color, shape, length, and activity of the sparks produced are observed (see Fig. 228).
4. *Blowpipe test:* The metal is melted with the welding blowpipe flame, and its behavior is observed.

Crystalline Structure of Metals and Alloys.—The crystalline structure of metallic substances results from the building up of the metals or alloys from a state of liquid solution.

To understand the formation of crystals, it must be recalled that everything is composed of atoms. In the fluid state, two or more atoms frequently combine to form molecules, but in this discussion all particles that go to build up crystals will be referred to as atoms.

As long as the fluid state persists, the atoms move freely among themselves. As a result, the liquid is mobile and yields easily to the slightest pressure. When freezing or solidification of the liquid takes place, the atoms are no longer free to move but bind themselves together into regular forms or definite patterns. These definite patterns consist of three-dimensional latticework of imaginary lines connecting the atoms and are known as *space-lattices.* The imaginary lines may be thought of as the bonds of force that hold the atoms approximately at the same distance from one another, thus preventing more than a limited freedom of movement among them with respect to one another.

The formation of space-lattices begins to take place at the cooling surface of the liquid mass. From there, it extends to the interior by conduction and convection of heat. The crystals grow by union and addition of space-lattices, but the size and formation of the crystals are influenced by the rate at which the heat is conducted away.

There are 14 types of space-lattice possible, but the great majority of metals crystallize according to only three: (1) the body-centered and

(2) face-centered types of the cubic system, and (3) the close-packed type of the hexagonal system (see Figs. 229 to 231). Among the metals that customarily assume the body-centered cubic form are chromium, columbium, iron, molybdenum, tungsten, and vanadium. Those which assume the face-centered form are aluminum, copper, gold, lead, nickel, platinum, and silver. Cadmium, cobalt, magnesium, titanium, and zinc are among those which have a close-packed hexagonal form.

Some metals are face-centered at one temperature and have the body-centered cubic form at another. Iron is a good example. This metal has a face-centered cubic lattice above 910°C. (1670°F.) and changes into the body-centered cubic form when cooled below that temperature. The changing from one type of space-lattice to another takes place in the solid state and without making much change in the volume or specific gravity of the mass. This is known as an *allotropic* change. Since in the body-centered type of space-lattice there are 9 atoms, whereas in the face-centered there are 14 atoms, it follows that when an allotropic change takes place there must be a rearrangement of atoms and space-lattices within the crystals.

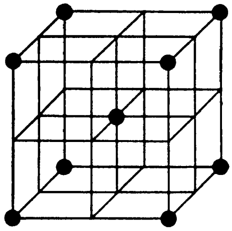


FIG. 229.—Body-centered cubic lattice.

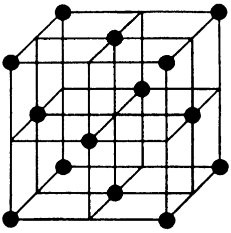


FIG. 230.—Face-centered cubic lattice.

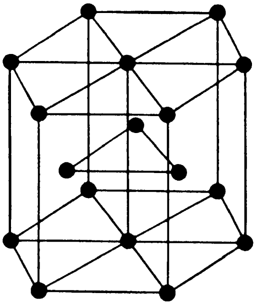


FIG. 231.—Hexagonal close-packed lattice.

The strength of a crystalline mass depends upon the cohesion within the individual crystals, and upon the adhesion of the crystals to one another. When a failure occurs, the mass ruptures at the weakest point. At atmospheric temperatures approaching their melting points, the same metals fail under tension by the tearing apart of the crystals from one another. In the liquid state, the mass has practically no coherence, and therefore the strength of the solid metal is a function of the sum total of the strengths of the interatomic bonds. Because of the nonuniform or haphazard arrangement of space-lattices, the interatomic bonds are not all acting directly against a force tending to produce rupture of the metal. If they were so acting, the tensile strength of the substance would amount to some millions of pounds per square inch.

An external strain applied upon a metallic mass causes, at first, a distortion of the space-lattices (see Fig. 232). When the external strain is removed, the space-lattices will resume their original shape, and thus no permanent deformation has taken place. Now, if the mass is still visualized as being made of a great many blocks, each block being made of millions of space-lattices, and if the strain is great enough, the distortion of the space-lattices will reach a point at which the individual blocks will slide over one another (see Fig. 233). This action is called *slippage along slip planes.* The yielding along the slip planes naturally causes a deformation of the crystals and, consequently, of the mass as a whole.

The elasticity of metals and alloys is produced by the elongation or compression of the interatomic bonds. After the external strain is removed, the bonds assume their original length. Therefore, the amount of elasticity depends upon the strength of the atomic bond in lengthening or shortening due to the temporary deformation of the space-lattice.

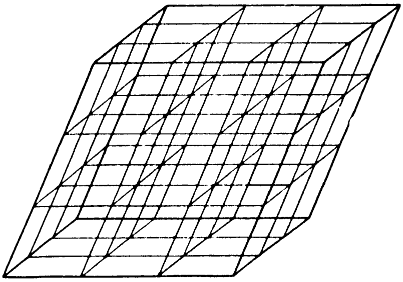


Fig. 232.—Representation of possible distortion of cubic space-lattices under strain.

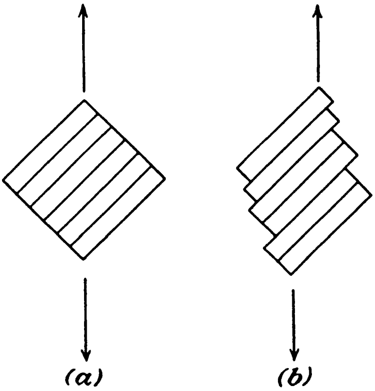


Fig. 233.—Diagrammatic representation of crystal deformation in a metal having cubic space lattices.

The resisting power of the interatomic bonds of a metal partly determines the resistance of a metal to penetration by another body.

The straining of a ductile material beyond its elastic limit, the subsequent removal of the strain, and its immediate reapplication will cause the metal to yield to further deformation and slippage without any elastic resistance. However, if the metal that has been strained beyond its elastic limit be allowed a short period of rest, it will be found that, upon retesting, the elastic limit will have increased over the original elastic limit. The ultimate strength will have increased, also. The length of time of the rest period required to produce the full result varies from several hours to several weeks, depending upon the metal. The action may be speeded by heating the metal.

All forms of cold-working of ductile metals produce deformation, as well as an actual breaking up and intermingling of the crystals. This results in a great increase in strength and in a still greater increase in elastic limit and hardness. This may be attributed to the fact that the broken portions (of the crystals) become wedged within the slip planes (see Fig. 234). This hinders further slippage of intracrystalline blocks, and finally no sliding will take place except under great strain. Thus, deformation does not occur easily, and the elastic limit of the metal is substantially increased. Also, the blocks do not yield easily to the penetration of other substances, and the mass has become considerably harder.

The *toughness* of metallic substances is measured by the amount of slip that occurs along slip planes within the crystals without resulting in rupture of the metal. It is the result of alternate slippings and wedgings, each wedge holding until a greater strain is felt. The successive wedging and slipping will produce deformation. In general, it may be said that tough metals and alloys are often the most malleable and ductile.

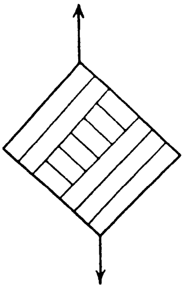


FIG. 234.—Wedging of slip bands.

The Constitution of Iron-Carbon Alloys.—Since even a brief discussion of the constitution of all individual metals and alloys would require much more space than is available in this volume, only the iron-carbon alloys will be treated.

As previously mentioned, iron is crystalline in structure, having the body-centered cubic lattice at one time and the face-centered at another. Each form is stable only within certain ranges of temperature. Between 1535°C. (2795°F.) and 1400°C. (2552°F.), the iron assumes the structure corresponding to a body-centered cubic lattice, this modification being referred to as *delta iron*. At 1400°C., a transformation occurs, and the iron assumes a face-centered cubic arrangement which persists down to 910°C. (1670°F.). This modification is called *gamma iron*. At 910°C., the body-centered cubic structure, now known as *alpha iron*, reappears and remains as such at all lower temperatures. With the appearance of each new crystalline form upon heating and cooling through one of the critical temperatures, there is a complete recrystallization.

Iron and carbon form a hard, brittle, crystalline compound known as iron carbide or cementite. When iron carbide is heated above 1100°C. (2012°F.), it decomposes rapidly into iron and graphite. Graphite, a distinct crystalline modification of the element carbon, is soft and easily pulverized.

Many metals have the ability to dissolve certain other elements in the solid state, solid solutions being thus formed. The dissolved elements will diffuse under suitable temperature conditions; and if sufficient opportunity for diffusion is allowed, physical and chemical homogeneity will be attained. In solid solutions, changes in chemical compositions do not necessarily bring about an abrupt change in physical properties.

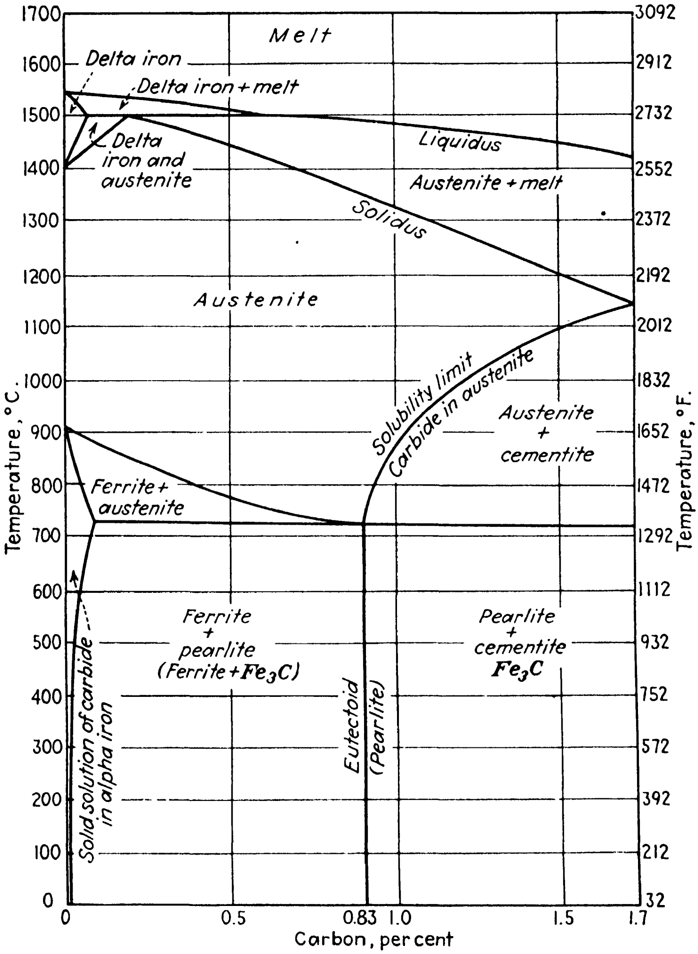


FIG. 235.—Iron-carbon constitutional diagram.

Alpha iron will hold in solid solution considerable amounts of various elements, such as nickel and silicon. The maximum solubility of carbon in alpha iron occurs at 723°C. (1333°F.) and decreases with a fall in temperature. A solid solution in which the alpha iron or the delta iron is the solvent is known as a *ferrite*. The term *austenite* is referred to those solid solutions in which the gamma iron is the solvent. A great deal of carbon may be dissolved in gamma iron.

The iron-carbon alloys may be classified according to whether the carbon content is below or above 1.7 per cent, this being the limit of the amount of carbon that will freeze in solid solution. Those alloys which contain less than 1.7 per cent carbon are generally called *steel,* and those which contain more are referred to as *cast irons.*

When steel is in a molten state, it is a liquid chemical solution of iron and carbon. As long as the carbon content does not exceed 1.7 per cent, upon freezing it becomes a solid solution of iron and carbon. Upon cooling through a range of temperatures, this solid solution decomposes in accordance with the carbon content. A solid solution that contains 99.17 per cent iron and 0.83 per cent carbon is the only solution that will cool as far as 700°C. (1292°F.) without decomposing. In all solid solutions containing carbon in excess of 0.83 per cent, iron carbide crystallizes out until the solution remaining when the alloy cools down to 700°C. contains only 0.83 per cent carbon. In all solid solutions containing more than 99.17 per cent iron, the iron crystallizes out until, upon cooling to 700°C., the solid solution contains no more than 99.17 per cent iron. Upon reaching this same temperature of 700°C., every solid solution of iron and carbon decomposes into grains of ferrite and iron carbide. Those grains which crystallize out at temperatures above 700°C. are large in size, whereas those which crystallize out at 700°C. are relatively small. Of course, in the above the cooling rate is assumed to be slow enough to permit the different changes to occur in a normal way. If the steel is heated instead of being cooled, a reverse change to that described takes place in each case.

The accompanying constitution diagram of iron-carbon alloys shows the constitution of each alloy upon slow cooling (see Fig. 235). This diagram is sometimes known as an "equilibrium" diagram, because the lines in it represent the places where one phase changes into another upon heating or cooling, as the case may be.

METALLURGY OF WELDS[1]

The study of metallurgy of welds requires a consideration of the chemical and physical effects incidental to fusion of the weld metal and of the changes due to the heat of welding in the weld region.

Thermal Conditions.—The general heat conditions that exist during fusion welding are shown diagrammatically in Fig. 236.

Depending upon the welding process used and upon the metal being welded, there exist wide variations in the maximum liquid temperature and in the slope of the temperature-gradient curve for the unfused metal. High degrees of superheat in the weld metal may be obtained in all fusion processes. The extent and slope of the thermal gradient is determined by the heat supplied by the welding process per unit volume of metal per unit time and by the heat capacity of the base-metal parts. The process used also determines the rate of cooling from the maximum temperature attained. Figure 237 shows examples of thermal gradients set up in some welding processes.

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[1] The material in this section has been condensed mainly from Chap. XXIII of the "Welding Handbook" of the American Welding Society.

Chemical Conditions.—In all fusion-welding processes, chemical reactions occur at the high superheat temperatures of the molten weld metal, and thus the weld-metal composition differs from that of the parent metal. These chemical reactions may occur between the molten metal and the gases of the atmosphere or between the molten metal and gases or other components of any protecting medium that may be provided. Also, oxidation of one or more of the weld-metal constituents may occur.

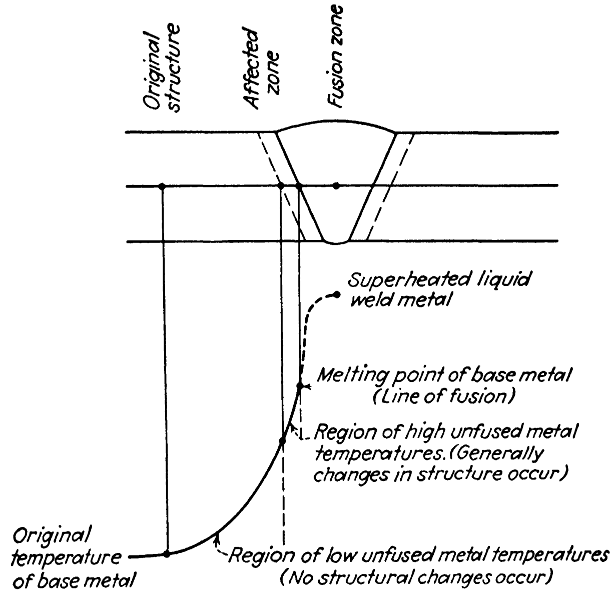
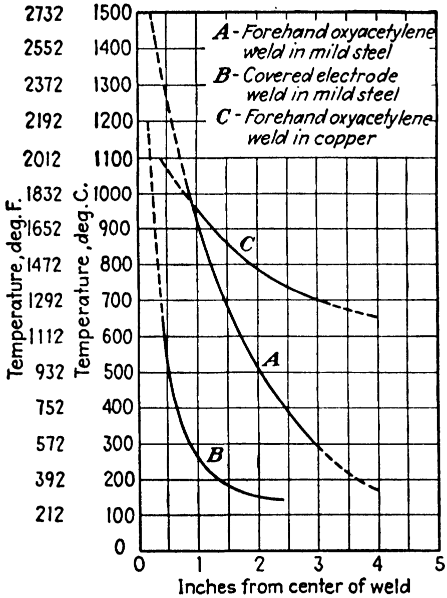

Original structure
Affected zone
Fusion zone
Superheated liquid weld metal
Melting point of base metal (Line of fusion)
Region of high unfused metal temperatures. (Generally changes in structure occur)
Original temperature of base metal
Region of low unfused metal temperatures (No structural changes occur)

FIG. 236.—Thermal conditions generally pertaining in a fusion weld.

Allotropic Transformation.—From the viewpoint of the physical metallurgist, metals and metal alloys may be grouped into two distinct classifications or divisions. These divisions are dependent upon the presence or absence of allotropic transformations that are likely to occur at any temperature up to the melting point.

Allotropic transformations consist in a lattice-structure rearrangement in which the atoms change from one geometrical configuration to another. Allotropic transformations are accompanied by recrystallization and other physical changes both upon heating and upon cooling through the temperature of the critical transformation (see Fig. 238*A*). Such alloys show variations in grain size in the heat-affected zone. The grain size is at its minimum at those points which have been heated to slightly above the transformation temperature and gradually increases toward the line of fusion (see Fig. 238*C*). The most common examples of this type are iron and steel.

The only effect of heating a pure, unstrained metal or alloy of the nontransformable type is an increase in grain size above the lowest temperature of recrystallization (see Fig. 238*B*). The heat-affected zone in such metals and alloys will show a gradual increase in grain size toward the line of fusion (see Fig. 238*D*).



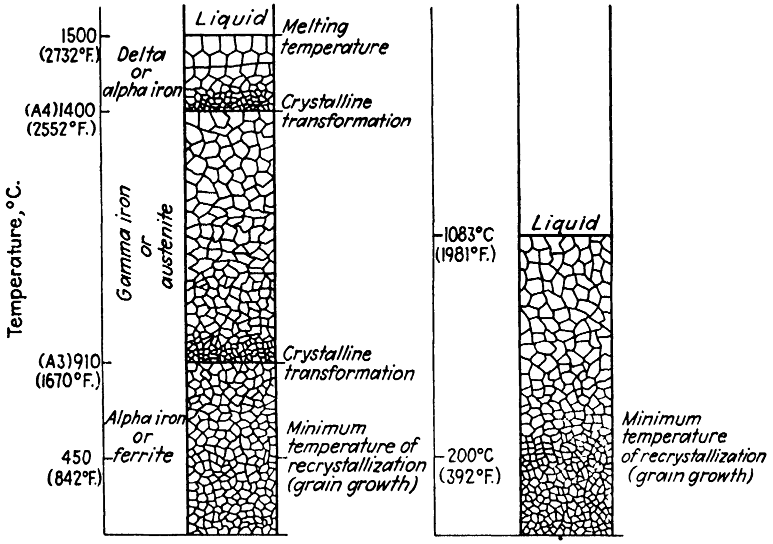
A and B compare thermal conditions for acetylene welding and arc welding in mild steel. A and C compare thermal conditions for acetylene welding for steel and copper (show effect of thermal conductivity differences)

FIG. 237.—Maximum temperature reached along a line perpendicular to three types of welds (0.39-inch plates, couples at mid-thickness). (*Porteven and Seferian.*)

Other Heat Effects.—Other heat effects may be shown by metal or alloys, such as the precipitation of a solute from a supersaturated solvent. For instance, carbide precipitation is caused by the heating of austenitic nickel-chromium alloy steels possessing a carbon content in excess of the saturation limit, approximately 0.02 per cent. This carbide precipitation causes intergranular corrosion of the affected zone of welds in these alloys.

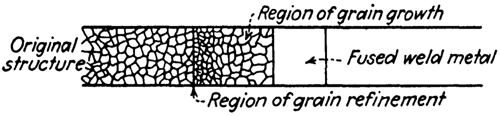
Another illustration is the embrittlement of the weld-affected zone of undeoxidized copper. The embrittlement is due to the precipitation of copper oxide at and within the grain boundaries as a result of the application of the heat of welding.

If the parent metal has been strained by cold-working, the application of the welding heat will cause recrystallization and change in the

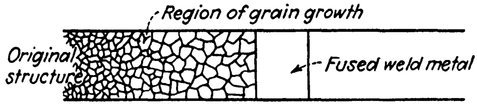


A Transformable metal (Pure iron)

B Non-transformable metal (Copper)



C Grain changes in affected zone of fusion weld in transformable metal



D Grain changes in affected zone of fusion weld in non-transformable alloy

FIG. 238.—Changes in grain size on heating metals with and without allotropic transformations.

properties of the original cold-worked material. Normally, this recrystallization in strained metals will occur at lower temperatures, so that the width of the heat-affected zone in welds on cold-worked material may be greater. Because of the larger grain size, the weld-affected zone of cold-worked material will possess lower hardness and tensile strength as compared with the original base metal.

Molten-metal Solidification.—After deposition, the molten metal solidifies in the fusion zone, and the solidification is accompanied by the formation of metallic crystals. The primary crystallization of pure metals occurs at constant temperature. In the case of alloys, solidification takes place through a range of temperature in which the alloy is a mixture of liquid and solid. During crystallization, the formation of dendrites, or treelike crystals, takes place. In fusion welds, the dendrites grow from the colder joint walls in a direction approximately at right angles to their walls, and the familiar columnar structure of the metal of single-pass welds (see Fig. 239*a*) is the result.

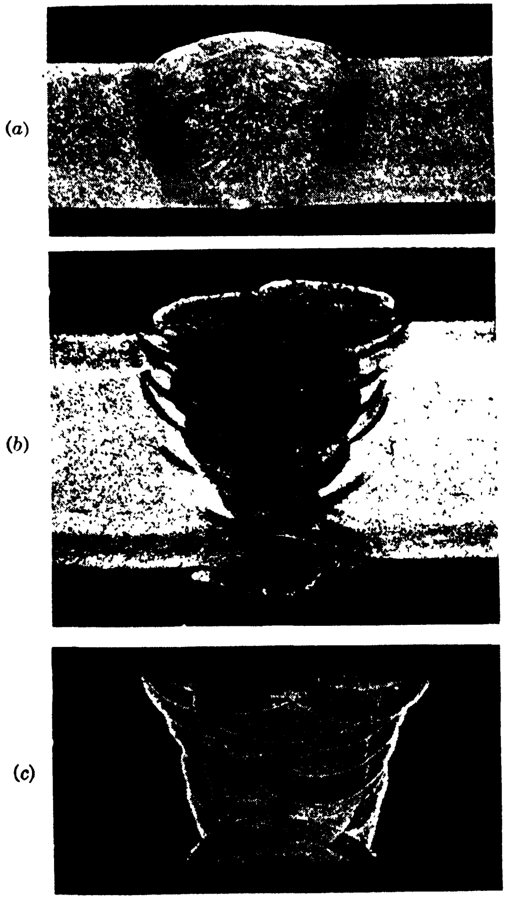


FIG. 239.—(*a*) Macrosection of single run high-current weld—1 in. plate. (Etched-ammonium persulphate.) (*b*) Macrosection of multiple-bead weld, showing weld layers and grain refinement of the weld metal. Also, heat effects in base metal. (Etched—1:1 HNO_3.) (*c*) Macrosection of multiple-bead weld showing weld layers and grain refinement of the weld metal. Also, heat effects in base metal. (Etched–1:3 HNO_3.) (*Courtesy of The Babcock & Wilcox Company.*)

Uniformity of Structure.—Welded joints are not strictly uniform, or homogeneous, either chemically or structurally. After welding, even though of identical chemical composition, the structure of the parent metal is dissimilar from that of the weld metal, unless the completed structure is mechanically worked while at high temperatures, which, for all practical purposes, is impossible. However, the aim is for an ideal condition, or one in which the properties throughout parent metal and weld metal are identical. From a practical viewpoint, the welds produced in many important commercial metals and alloys may be considered as homogeneous; for their mechanical properties, throughout the weld zones, are similar if not identical.

The Metallurgy of Low-carbon Steel Welds.—The metallurgy of fusion welding consists of a study of the following: (1) changes in chemical composition while the weld metal is in the molten state; (2) the macro- and microstructural features of the fused weld metal and adjacent parent metal produced by the high temperatures attendant on the melting and solidification of the metal; (3) the variations in the mechanical properties of welded joints throughout a range of temperature as affected by chemiical composition of the weld metal, the structural features of the weld joint, and subsequent heat-treatment.

Changes in Chemical Composition.—In some welding processes the molten metal is exposed to the gases of the atmosphere. A chemical reaction takes place between the molten metal and these gases. The extent of the chemical reaction depends upon the maximum temperature attained, the time interval of the molten phase, the surface of the molten metal exposed, and the degree of protection afforded the molten metal from the gases by varying conditions associated with each welding process.

In bare-electrode welding, maximum amounts of nitrogen and oxygen are to be found. At times, welds made by this process show a nitrogen content as high as 0.15 per cent and an oxygen content as high as 0.26 per cent. Progressively lower values are obtained if the weld metal is deposited under a protective blanket of slag or flame, which may vary in efficiency as protective media (see Table XX).

Other gases that may come in contact with the molten metal are hydrogen, water vapor, carbon dioxide, and carbon monoxide. All these are readily dissolved in the molten steel. When solidification takes place, a large proportion of these gases is thrown out of solution; and if these are not permitted to escape, porosity in the weld metal may result.

Structural Features.—A coarse-grained columnar structure results when a single bead of weld is deposited (see Fig. 239*a*). With low-carbon steels, the coarse grains may be refined by reheating through the critical range. Such refinement takes place when multiple beads are

TABLE XX.—CHEMICAL ANALYSES OF METALLIC-ARC WELD METALS AND CHANGE IN COMPOSITION FROM ORIGINAL ELECTRODES

Weld type	Degree of protection	Carbon, per cent	Loss over original electrode, per cent	Manganese, per cent	Loss over original electrode, per cent	Nitrogen,* per cent	Gain over original electrode, per cent
(1) Original electrode	....	0.13–0.18	..	0.40–0.60	..	0.005	
(2) Bare electrode	None	0.021	88	0.22	60	0.125	2,400
(3) Covered electrode, slag producing, long arc	Minimum	0.06	63	0.30	40	0.07	1,300
(4) Covered electrode, slag producing, medium arc	Medium	0.10	37	0.36	28	0.05	900
(5) Covered electrode, slag producing, short arc	Good	0.11	31	0.41	18	0.027	440
(6) Covered electrode, slag producing, short arc plus gas flame	Maximum	0.11	31	0.43	14	0.015	200
(7) Bare electrode, gas protection	Good	0.08	50	0.50	0	0.031	520
(8) Covered electrode, gas producing	Maximum	0.075	55	0.50	0	0.019	280
(9) Bare electrode. Arc buried in powdered flux in groove	Maximum	0.07	52	0.33	34	0.011	120
Boiler-plate	....	0.15–0.30	..	0.30–0.60	..	0.008	

* By modified Allen solution method of Jordan and Swindells.

deposited, the heat of each succeeding bead reheating the previously deposited bead and refining the grain of such portions of the weld layers as are reheated above the critical-temperature range (see Fig. 239*b*, *c*).

Theoretically, the deposition of succeeding beads may be controlled so as completely to refine the bead previously deposited. But, in practice, this is seldom accomplished; for the first reheating to above the critical temperature does not penetrate all of the bead, and thus localized coarse-grained structures exist in the weld metal at the bottom of each bead.

The Nitride Constituent.—The solid solubility of nitrogen in iron at room temperature is extremely small. Weld metals possessing nitrogen contents above room-temperature solubility value precipitate the excess nitrogen as iron nitride in the ferrite grains when cooled slowly from high temperatures.

Precipitated nitrides lower the corrosion resistance of the weld metal. With an increase in nitrogen content, there are an increase in hardness, yield, and tensile strength and a pronounced loss in ductility and impact resistance.

The relative increases in tensile strength and yield strength and the decreases in elongation and reduction of area values for high- and low-nitrogen weld metals may be obtained by referring to Fig. 241.

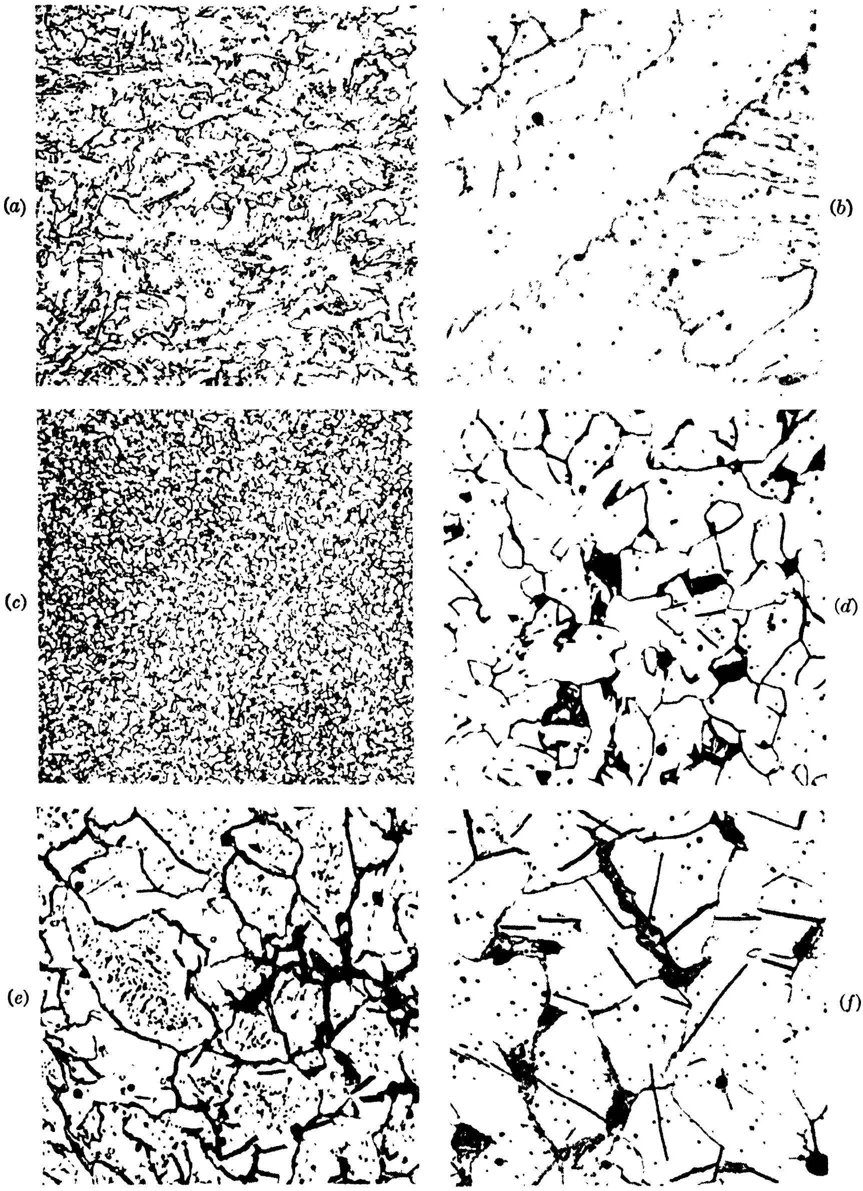


FIG. 240.—(*a*) Coarse-columnar structure in as-deposited low-carbon steel coated electrode weld metal. 100-× (reduced ½). (*b*) Coarse-columnar structure in as-deposited low-carbon steel coated electrode weld metal. 500-× (reduced ½). (*c*) Low-carbon steel weld metal refined by the heating effect of the succeeding bead. 100-× (reduced ½). (*d*) Low-carbon steel weld metal refined by the heating effect of the succeeding bead. 500-× (reduced ½). (*e*) Highly dispersed nitrides in a low-carbon steel weld metal. 500-× (reduced ½). (*f*) Well-defined nitride needles in a low-carbon steel weld metal. 500-× (reduced ½). (*Courtesy of The Babcock & Wilcox Company.*)

Annealing of Low-carbon Weld Metals.—When low-carbon weld metals are annealed, the following metallographic changes take place:

1. Upon reheating the weld metal to 900°C. (1650°F.), the coarse cast columnar structure of localized zones no longer persists, and the crystals become completely equiaxed.

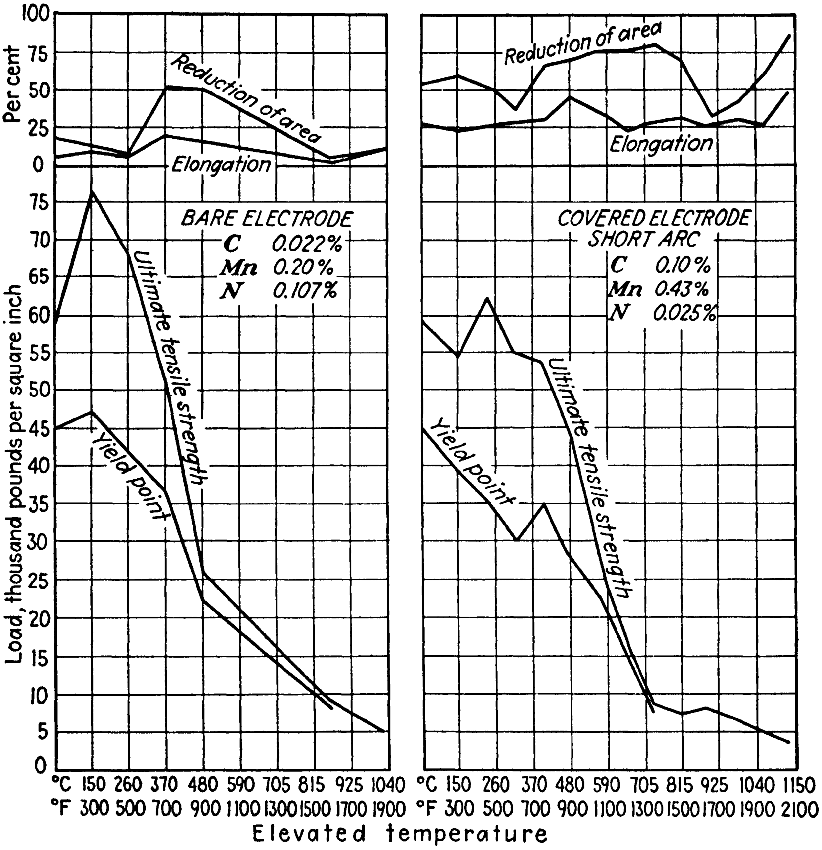


FIG. 241.—Tensile properties of bare and covered electrode welds at elevated temperatures.

2. Rapid grain growth takes place above 900°C., and there is a marked difference in the size of the grains on weld metals reheated to 900 and 1000°C. (1830°F.).

3. The nitride needles are better defined and more pronounced with higher annealing temperatures.

4. Marked coagulation of the oxide constituent of the bare electrode weld metal occurs at temperatures above 910°C. (1670°F.), the small rounded oxide inclusions being very pronounced after annealing from 1000°F.

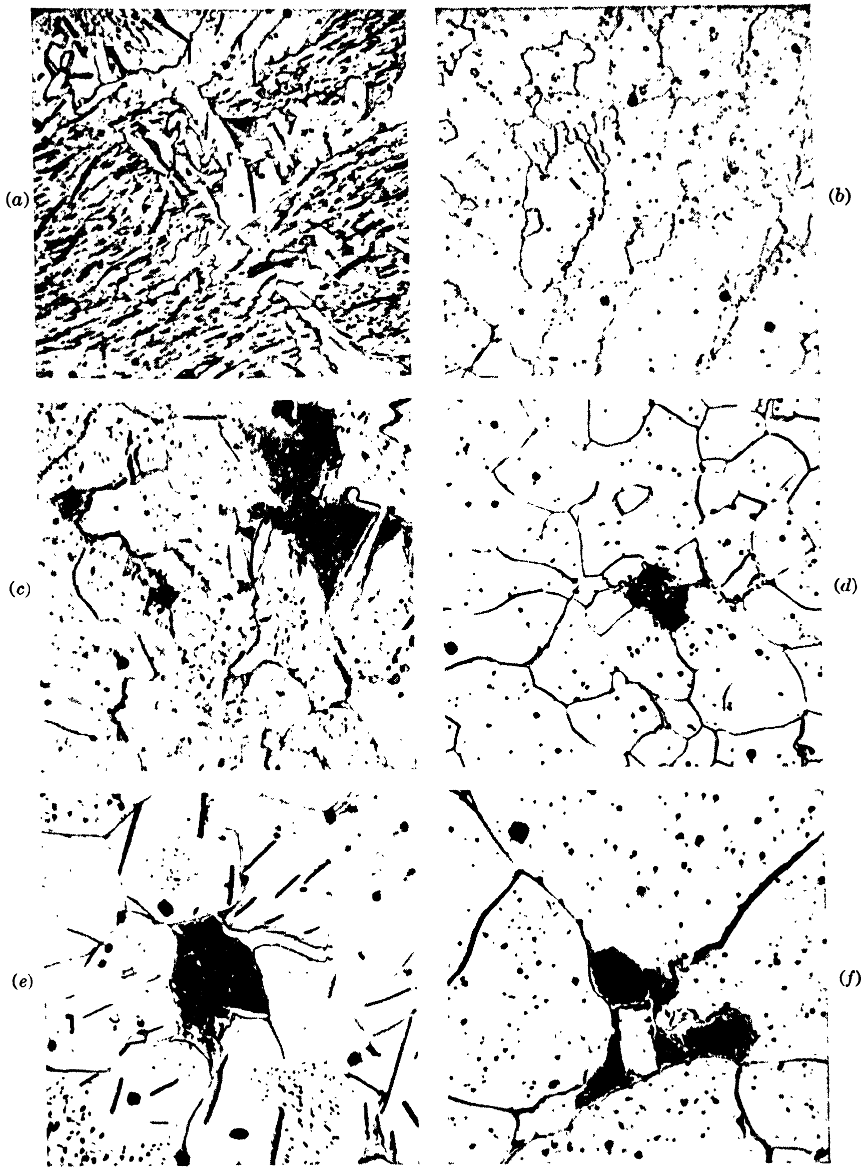


FIG. 242.—(*a*) Columnar structure persists in a bare electrode low-carbon steel weld metal after annealing at 800°C. (1470°F.). (*b*) Columnar structure persists in a coated electrode low-carbon steel weld metal after annealing at 800°C. (1470°F.). (*c*) Equiaxed structure in a bare electrode low-carbon steel weld metal after annealing at 900°C. (1650°F.). (*d*) Equiaxed structure in a coated electrode low-carbon steel weld metal after annealing at 900°C. (1650°F.). (*e*) Coarse-grained equiaxed structure in a bare electrode low-carbon steel weld metal showing nitride eutectoid (braunite), nitride needles and rounded oxide inclusions. Annealed 1000°C. (1830°F.). (*f*) Coarse-grained equiaxed structure in a coated electrode low-carbon steel weld metal showing pearlitic constituent. Annealed 1000°C. (1830°F.). (All photomicrographs at 500-× (reduced ½), etchant—4 per cent nital. (*Courtesy of The Babcock & Wilcox Company.*)

These changes are illustrated in Fig. 242.

Annealing results in a decrease in hardness, ultimate strength, and yield strength. The reduction in ultimate strength is less pronounced than that in yield strength (see Fig. 243). The ductility of bare-wire weld metal is not appreciably increased by annealing, but the ductility of the covered-electrode weld metal is considerably increased.

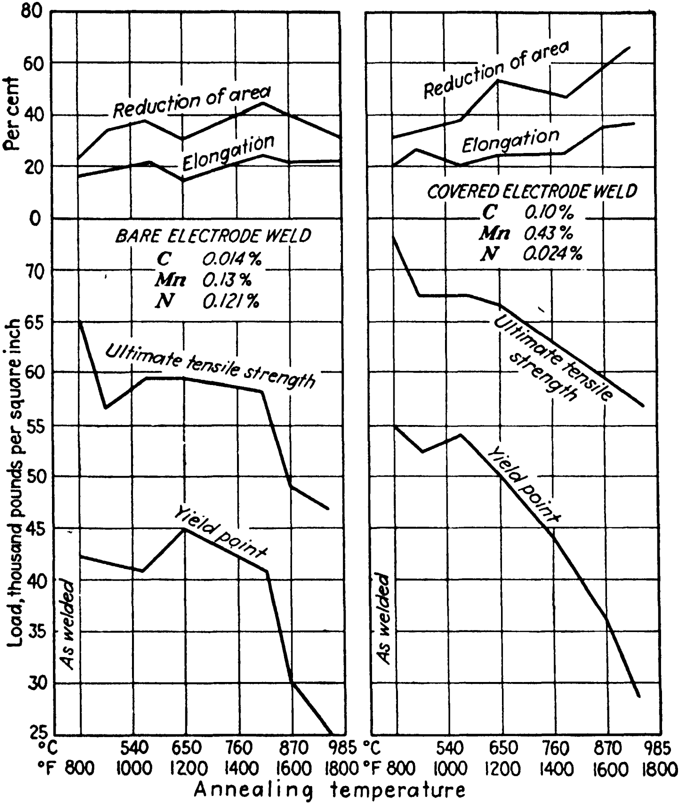


FIG. 243.—Tensile properties of bare and covered electrode welds as welded and after annealing at temperatures indicated.

The gradual decrease in strength and hardness of the welds on cooling from progressively higher temperatures up to 600 to 700°C. (1110 to 1290°F.) is due mainly to the relief of residual welding stresses rather than to structural changes. Redistribution of the carbide and nitride constituents undoubtedly occurs at these lower annealing temperatures, but no changes in grain size occur until an annealing temperature of 800 to 900°C. (1470 to 1650°F.) is reached. With annealing temperatures over 800°C., the decrease in hardness and yield strength is due to an increase in grain size of the ferrite.

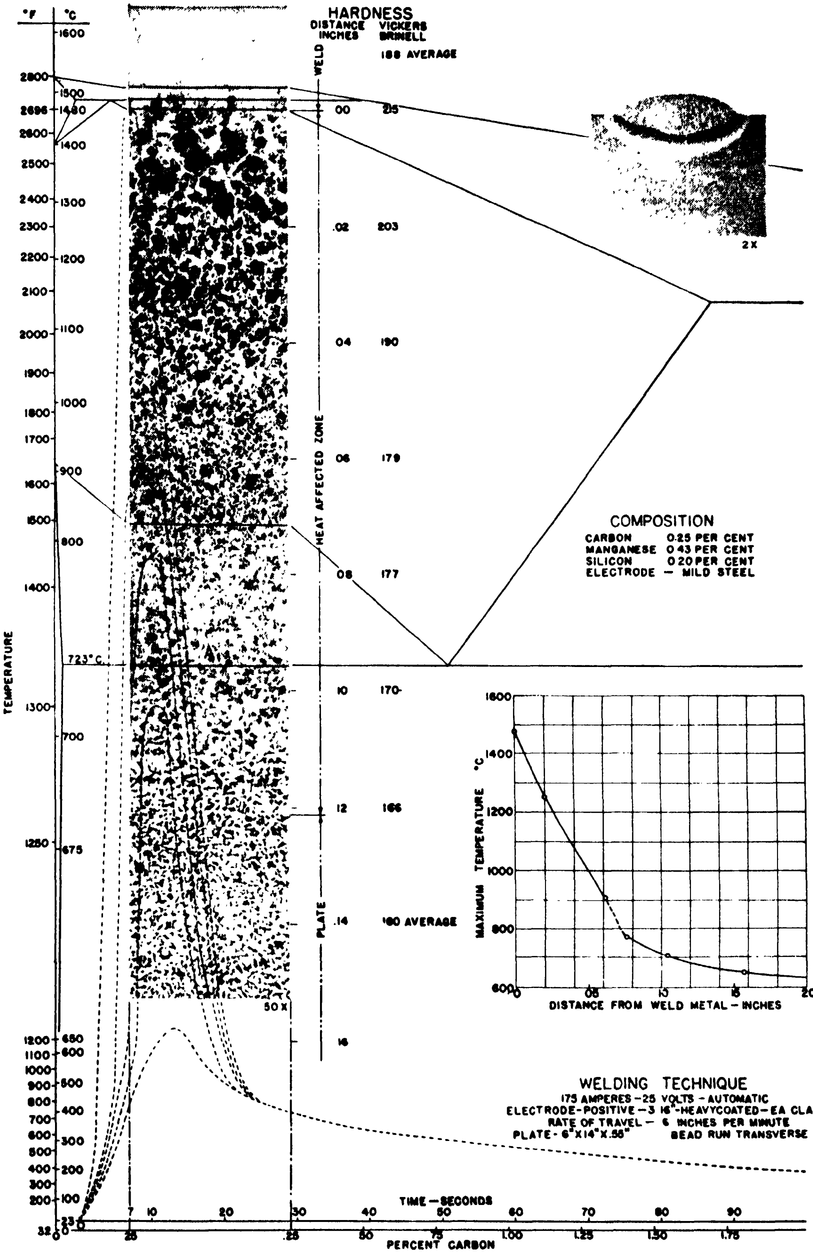


FIG. 244.—Relation of thermal conditions, structure, and hardness in arc welding mild carbon steel. (*Courtesy of Naval Research Laboratory, Anacostia Station.*)

When heat-treatment is carried out for stress-relieving purposes only, the usual temperature of approximately 620 to 650°C. (1150 to 1200°F.) is not sufficiently high to effect changes in grain size.

Mechanical Properties of Low-carbon Weld Metals.—The mechanical properties of a weld metal are a direct result of the chemical composition of the weld and of the heat-treatment that the solidified metal has undergone. The mechanical properties of weld metals often vary considerably with each welding process, and even when the same process is used, because of the many variables involved in each process. Figure 243 shows the combined effect of changes in chemical composition and differences in heat-treatment on the tensile properties of two types of metallic-arc-welded metals.

In general, all usual commercial welding processes can be controlled so as to produce weld metal whose mechanical properties are practically similar to those of the usual grades of low-carbon parent metals. For instance, the impact values of low-carbon weld metals deposited by shielded arc are similar throughout a range of temperature to those of plain-carbon-steel base metal of approximately 0.25 per cent carbon. And if the weld metal is free from gross defects, such as porosity, lack of fusion, cracks, and so on, the fatigue or endurance limit of low-carbon weld metals is similar to that of low-carbon parent metal (25,000 to 32,000 lb. per sq. in.).

Heat-affected Zones.—When weld metal is deposited, affected zones in parent metal will be found adjacent to each line of fusion. This affected zone is a region that has been heated to a sufficiently high temperature to cause a change in microstructure. This change varies in accordance with the maximum temperature attained in the thermal gradient that exists back from the line of fusion. With deposited single beads, the affected zone shows a gradation in structure varying from a coarse overheated structure adjacent to the line of fusion to a full-grained zone corresponding to the critical point whose temperature is 910°C., to a partly spheroidized zone of granular pearlite corresponding to 720°C., to the original unaffected ferrite-pearlite structure of normalized or annealed mild steel (see Fig. 244).

The depth of the heat-affected zone varies with the thermal conditions of individual welds, but the same gradation of structure will exist in all welds.

In multiple-bead welds the heat-affected zone is subjected to successive heatings and coolings, in a manner similar to that of the individual layers. The microstructure at any point will have a grain size corresponding to the maximum temperature above the critical range last attained. As a result, there is a softening of the affected region hardened by original weld deposition.

The variations in the chemical composition of the parent metal and in the rate of cooling from temperatures produced by welding heat will greatly influence the structure and properties of the weld-affected zone

CHAPTER XIV

TESTING AND INSPECTION OF WELDS

The application of fusion welding to the fabrication of structures whose failure due to improper welding would constitute a hazard has brought about the development and the adoption of tests governing the qualifications of welding operators or the quality of the welding performed.

These tests may be of the destructive or nondestructive type. The destructive tests supply quantitative information. The nondestructive tests are indicative of quality alone; as a matter of fact, some of them are indicative only to a limited extent.

The destructive tests include tensile, bend, nick-break, impact, fatigue, specific-gravity, hardness, and drift and crush tests. Among the nondestructive tests are visual examination, hydraulic and air tests, and stethoscopic, X-ray, gamma-ray, reheating, and magnetic tests.

Welding authorities are usually in full agreement on the properties to be determined and on the test procedures in general, but all too often they differ widely on the shape and size of the specimens and the details of the test procedure. In this discussion, the instructions issued and recommended by the International Acetylene Association and the American Welding Society are used as a reference. The illustrating sketches have been taken mainly from literature published by these bodies.

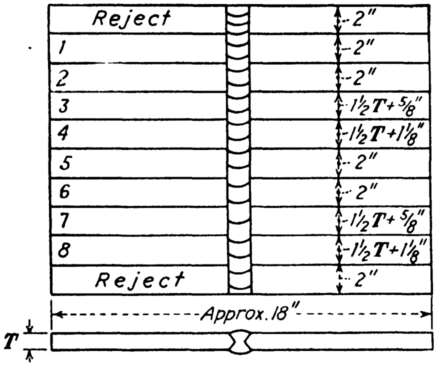
DESTRUCTIVE TESTS

Destructive tests may involve destruction of a complete welded unit or may require specimens cut from a unit that has been selected as representative.

A typical required division of a test plate and the locations of the test specimens, often referred to as "coupons," are shown in Fig. 245. The type of joint, the preparation of the edges, and the welding procedure used for the test plate must be the same as that employed for the construction.

Tensile Test.—The tensile test consists in causing the welded specimen to fail by applying a measured load. In conformity with the standard for flat specimens set by the American Society for Testing Materials (A.S.T.M.), the coupon is usually taken transversely with the weld located in the center of the specimen (see Fig. 246).

The weld reinforcement may or may not be removed, depending upon the type of information wanted. If the reinforcement is removed and if the failure occurs in the weld, the unit strength of the weld metal is obtained; if the failure occurs outside the weld and the heat-affected zone, the weld metal is seemingly stronger than the parent metal. When the reinforcement is not removed, the test reveals whether or not the joint is stronger than the plate.



1 and 5, full sect. tens. test 3 and 7,-nick break test
2 and 6, red. " " " 4 and 8,- free bend test

FIG. 245.—Test-plate dimensions and specimen locations.

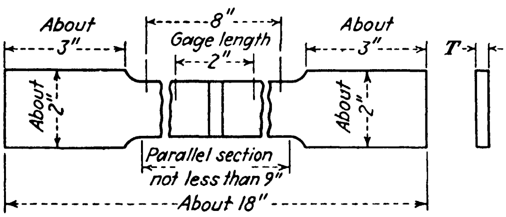


FIG. 246.—Full-section tensile-test specimen.

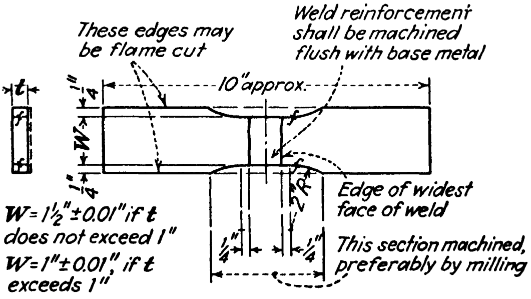

These edges may be flame cut
Weld reinforcement shall be machined flush with base metal
10" approx.
t
W
Edge of widest face of weld
This section machined, preferably by milling
W = 1½" ± 0.01" if t does not exceed 1"
W = 1" ± 0.01" if t exceeds 1"
¼"
¼"

FIG. 247.—Reduced-section tensile-test specimen (plate).

If the weld metal is stronger than the plate, the strength of the weld may be determined by using a short- or reduced-section tensile-test specimen, where the fracture is forced to take place in the weld (see Figs. 247 and 248).

During a tensile test, other factors besides tensile strength may be measured, such as yield point, elongation, and reduction of area. The yield point is reached when the metal continues to stretch without further increase in the applied load. The exact value of the yield point of the weld metal cannot be easily determined, for it differs from the yield point of the parent metal, and over any reasonable gauge length a combination of weld metal and parent metal exists. The elongation figure is of little value, especially when the test of the weld metal in such cases is best obtained by means of the free bend test.

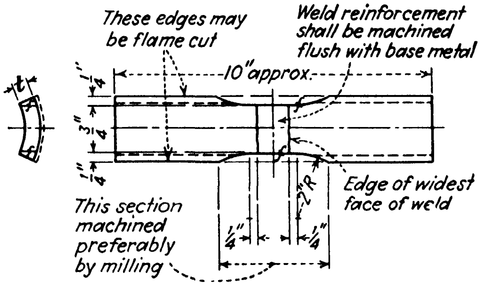

These edges may be flame cut
Weld reinforcement shall be machined flush with base metal
10" approx.
t
This section machined preferably by milling
Edge of widest face of weld
1/4"
1/4"

Fig. 248.—Reduced-section tensile-test specimen (pipe).

If it is desired to obtain the intrinsic value of the tensile strength, yield point, and elongation and reduction of area of the weld metal only, the all-weld metal specimen is taken longitudinally. The specimen may be prepared by butting together two J-grooved plates (see Fig. 249) and filling the groove. The specimen is then machined as in Fig. 250.

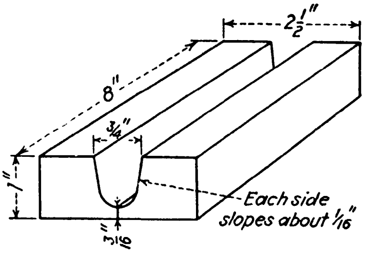


Fig. 249.—Steel plates welded together for making tensile-test specimen.

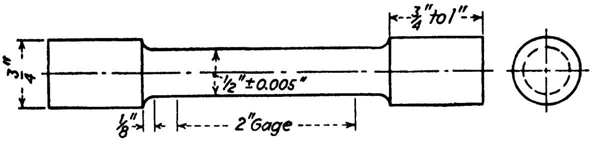
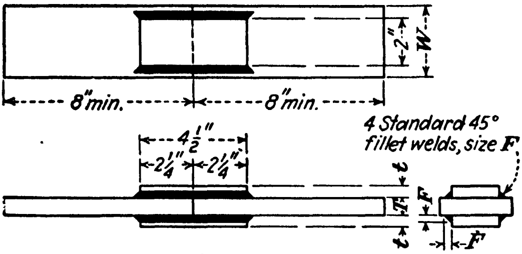


Fig. 250.—All-weld metal tension test piece.

In the case of fillet welds, a tension test is commonly applied to a specimen formed by fillet-welding two splice bars to opposite sides of two butted test bars. The fillet welds are made either longitudinally or transversely along the edges of the splice bars. In either instance, the welds fail in shear, and the stress is recorded in pounds per lineal inch (see Figs. 251 to 253).

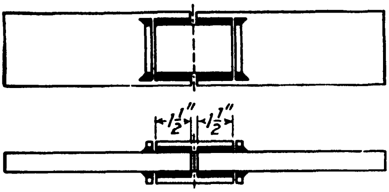
Tensile testing usually requires a special machine. These machines may be either power-driven or hand-operated. The test specimen is clamped in the jaws of the machine (see Fig. 254); the load is slowly applied; and as the fracture occurs, the reading is taken on an attached balance or pressure gauge.



Dimensions

Size of weld F, in.	⅛	¼	⅜	½
Thickness t, in.	⅜	½	¾	1
Thickness T, in.	⅜	¾	1	1¼
Width W, in.	3	3	3	3½

FIG. 251.—Longitudinal fillet-weld shearing test specimen after welding.



Note - For other dimensions see FIG. 251

FIG. 252.—Longitudinal fillet-weld shearing test specimen after machining.

The tensile strength in pounds per square inch may be obtained by dividing the maximum load, registered in pounds, by the cross-sectional area of the specimen, measured in square inches. The cross-sectional area of a flat specimen is obtained by multiplying the width by the thickness; that of a round specimen by multiplying the squared radius by 3.1416.

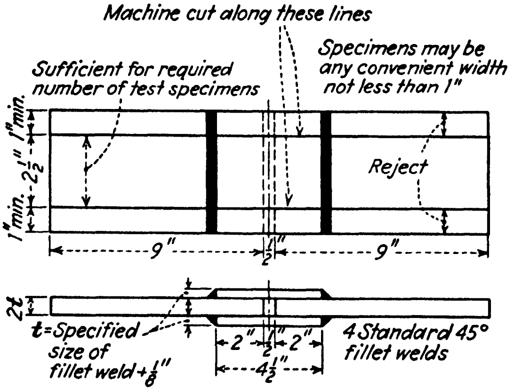

Machine cut along these lines
Sufficient for required number of test specimens
Specimens may be any convenient width not less than 1"
1" min.
2½"
1" min.
Reject
9"
½"
9"
2t
t
t=Specified size of fillet weld+⅛"
2"
½"
2"
4½"
4 Standard 45° fillet welds

FIG. 253.—Transverse fillet-weld shearing-test specimen.

Special charts are often supplied for the quick calculation of ultimate tensile strengths (see Chart II).

Bend Tests.—These tests may be subdivided into free-bend tests and guided-bend tests.

The *free-bend test* is used to determine the ductility of the welded joint. The test yields quantitative data independent of the thickness and width of the specimen, provided that the width is not less than 1½ times the thickness.

The design of the free-bend specimen is as shown in Figs. 255 and 256

The method of preparation may be either as in Fig. 257 or in Fig. 258. After making the preliminary bends, the specimen is placed as a strut in a vise or press (see Fig. 259). It is then bent until failure occurs on the outside bent surface between the gauge marks. If no cracks or depressions appear, the specimen is bent double. Corner cracks are not considered as failures. Any crack or depression on the surface is not considered as a failure until it exceeds a specified size in any direction, which is usually about $\frac{1}{16}$ in. or more.

The elongation may be determined by measuring the minimum distance between the gauge lines, along the convex surface of the weld, to the nearest 0.01 in. and subtracting the initial gauge length. The percentage elongation may be obtained by dividing the elongation by the initial gauge length and multiplying by 100. The actual measurements may be conveniently taken by using a flexible steel scale graduated in hundredths of an inch and a magnifying glass. If direct measurements are not possible, the elongation may be calculated from the curvature by the formula $100t/2R$, where t is the thickness and R the radius to the neutral plane. A bend extensometer may also be used to measure ductility.

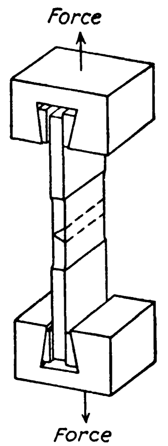


FIG. 254.—Tensile test specimen clamped between jaws of tensile test machine.

The *guided-bend tests* are used to reveal lack of soundness in the welded joint.

In the *root-bend test*, the specimen is bent backward, so as to stretch the bottom of the Vee of a single-Vee weld (see Fig. 261). It is particularly effective in revealing lack of penetration and soundness at the bottom of the Vee.

In the *side-bend test*, the bending takes place in a thin specimen taken transversely across the welded joint so that the length of the weld is perpendicular to the plane specimen (see Fig. 262). It is used mainly to reveal lack of side-wall fusion in the Vee or groove.

In all guided-bend tests, the specimen is bent in a jig substantially in accordance with Fig. 263. The specimen is placed on the female member of the jig with the weld at mid-span. The two members of the jig are then forced together by any convenient means, until the proper curvature is obtained.

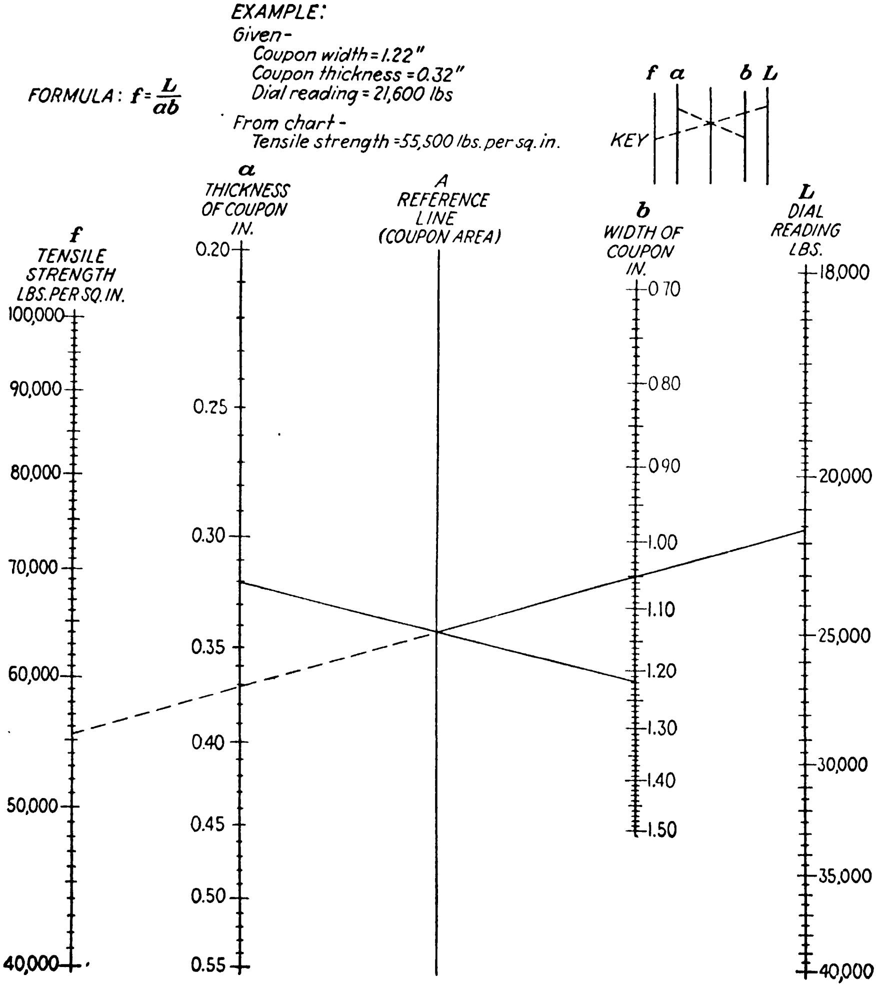
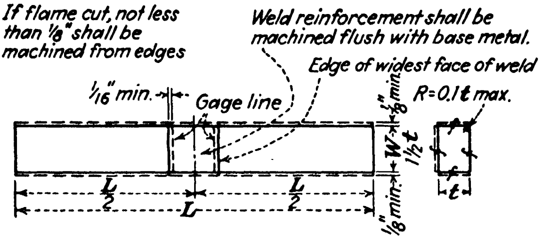


CHART 2.—Nomographic chart for calculating ultimate tensile strength. (*Courtesy of The Linde Air Products Company.*)

The convex surface of the specimen is examined for the appearance of cracks exceeding a specified size measured in any direction. If any such cracks are present, the specimen is considered as having failed.

Nick-break Test.—This test, simple and inexpensive to make, consists in rupturing a specimen notched in the weld, with a force that, unless


If flame cut, not less than 1/8" shall be machined from edges
Weld reinforcement shall be machined flush with base metal.
Edge of widest face of weld
1/16" min.
Gage line
1/8" min.
R=0.1t max.
W=1 1/2 t
L/2
L/2
L
1/8" min.
t

Dimensions

t = in.	1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 1/2	2	2 1/2
W = in.	3/8	9/16	3/4	15/16	1 1/8	1 1/2	1 7/8	2 1/4	3	3 3/4
L min., in.	6	8	9	10	11	12	13 1/2	15	18	21
B*min., in	1 1/4	1 1/4	1 1/4	2	2	2	2	2	2	3

* See FIG. 258

Note: The length **L** is suggestive only, not mandatory

FIG. 255.—Free-bend test specimen (plate).

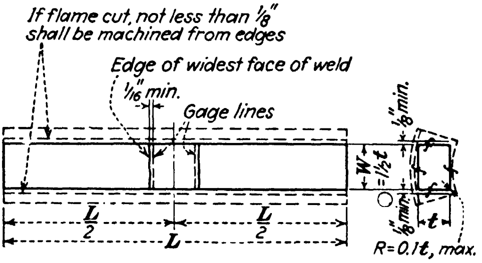

If flame cut, not less than 1/8" shall be machined from edges
Edge of widest face of weld
1/16" min.
Gage lines
1/8" min.
W=1 1/2 t
1/8" min.
t
L/2
L/2
L
R=0.1t, max.

FIG. 256.—Free-bend test specimen (pipe).

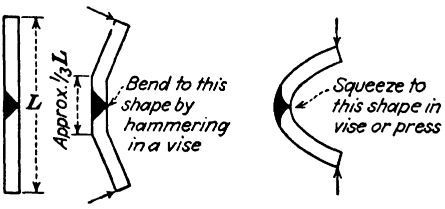

L
Approx. 1/3 L
Bend to this shape by hammering in a vise
Squeeze to this shape in vise or press

FIG. 257.—One method by which free-bend test coupon may be bent.

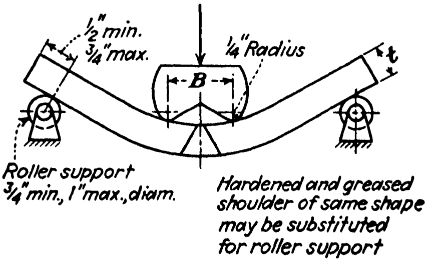

1/2" min.
3/4" max.
1/4" Radius
B
t
Roller support 3/4" min., 1" max., diam.
Hardened and greased shoulder of same shape may be substituted for roller support

FIG. 258.—Another method for initial bend for free-bend test specimens.

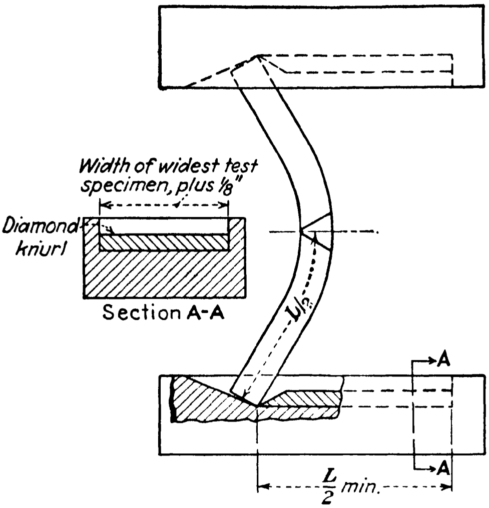


FIG. 259.—Recommended fixture for final bending of free-bend test specimens.

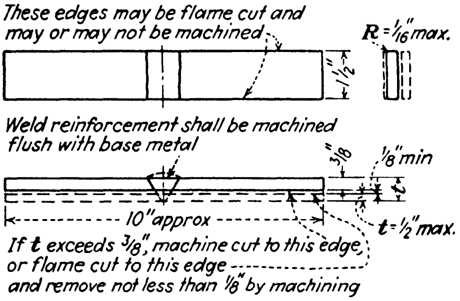
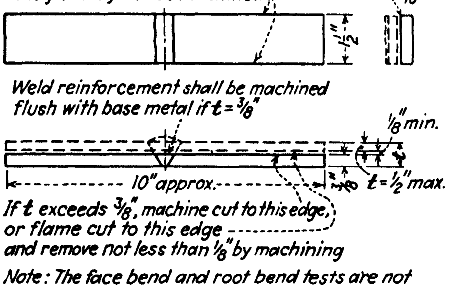

These edges may be flame cut and may or may not be machined
R = 1/16" max.
1 1/2"
Weld reinforcement shall be machined flush with base metal
3/8"
1/8" min
t
10" approx
t = 1/2" max.
If t exceeds 3/8", machine cut to this edge,
or flame cut to this edge
and remove not less than 1/8" by machining

FIG. 260.—Face-bend test specimen.


These edges may be flame cut and may or may not be machined
R = 1/16" max.
1 1/2"
Weld reinforcement shall be machined flush with base metal if t = 3/8"
1/8" min.
t
10" approx.
3/8"
t = 1/2" max.
If t exceeds 3/8", machine cut to this edge,
or flame cut to this edge
and remove not less than 1/8" by machining

Note: The face bend and root bend tests are not applicable if the plate thickness **t** *is less than 3/8"*

FIG. 261.—Root-bend test specimen.

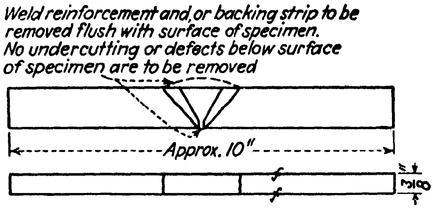

Weld reinforcement and/or backing strip to be removed flush with surface of specimen.
No undercutting or defects below surface of specimen are to be removed
Approx. 10"
f
f
3/8

FIG. 262.—Side-bend test specimen.

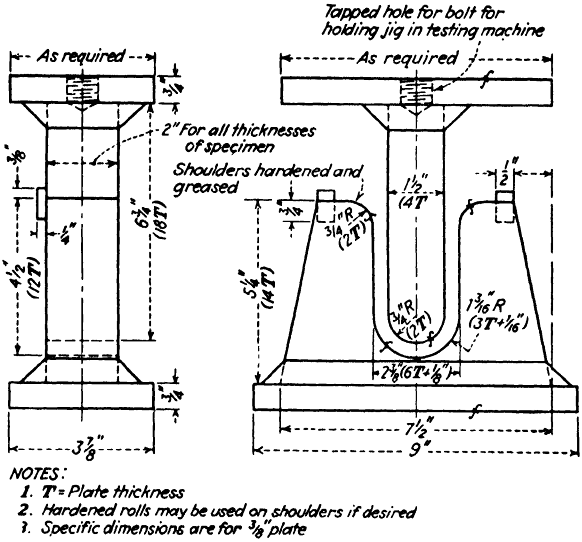

Tapped hole for bolt for holding jig in testing machine
As required
As required
f
3/4
2" For all thicknesses of specimen
Shoulders hardened and greased
3/8
1/4"
4 1/2 (12T)
6 3/4 (18T)
3/4
3 7/8"
1/2"
1 1/2" (4T)
3/4 (2T) R
5 1/4 (14T)
3/4 R (2T)
1 3/16 R (3T+1/16)
f
2 3/8" (6T+1/8")
f
7 1/2"
9"
NOTES:
1. T = Plate thickness
2. Hardened rolls may be used on shoulders if desired
3. Specific dimensions are for 3/8" plate

FIG. 263.—Guided-bend test jig.

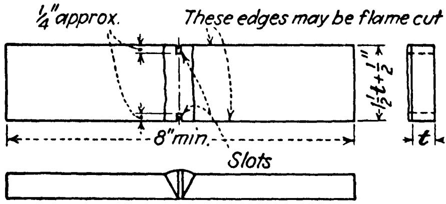


FIG. 264.—Nick-break test specimen (plate).

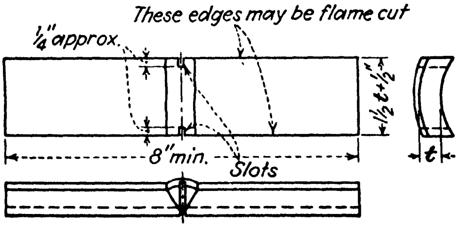
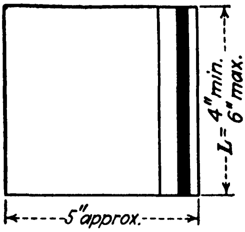


FIG. 265.—Nick-break test specimen (pipe).

otherwise specified, may be applied either slowly or suddenly as by one or more blows of a hammer.

The nick-break test is a homogeneity test and indicates the soundness of the weld by showing on the fractured surface the extent of the penetration obtained, the presence of oxide or slag inclusions, and the degree of porosity. No more than six gas pockets or holes per square inch of fractured surface may be present. The maximum dimension of any defect may not be larger than $\frac{1}{16}$ in.

The width of the specimen should be equal to $1\frac{1}{2}$ times the thickness. The slots at each end of the specimen may be made with a hack saw and should not be deeper than $\frac{1}{4}$ in. No machining of the specimen is necessary (see Figs. 264 and 265).



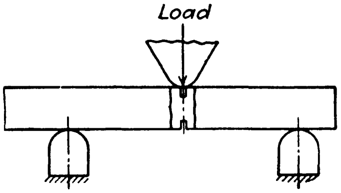


Fig. 266.—Method of rupturing nick-break test specimens.

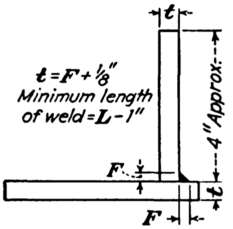


Fig. 267.—Fillet-weld-break test specimen.

In the case of fillet welds, a test equivalent to the nick-break test is applied to a so-called fillet-weld-break specimen (see Figs. 267 and 268).

The specimen is formed by fillet-welding one flat plate or bar at right angles to another, in such a manner that by application of pressure or a blow to one edge of the specimen the fillet weld may be opened up at its root. Any lack of penetration or soundness is revealed by the resulting fracture.

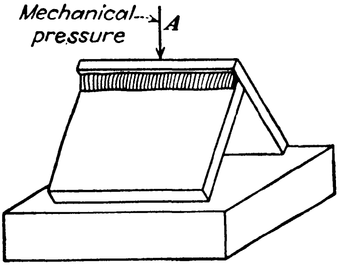


Fig. 268.—Method of rupturing fillet-weld-break test specimen.

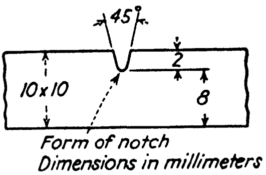


Fig. 269.—The Izod test specimen.

Impact Test.—To determine the impact value of welds and base metal in welded products to be used at low temperatures, a suitably prepared specimen is placed in a fixture, and a pendulum or weight is allowed to strike against it, causing distortion or failure of the specimen. The energy lost by the pendulum is measured at the same time.

Although several methods have been developed for determining the impact properties of metals, the two most widely used are the Izod and the Charpy.

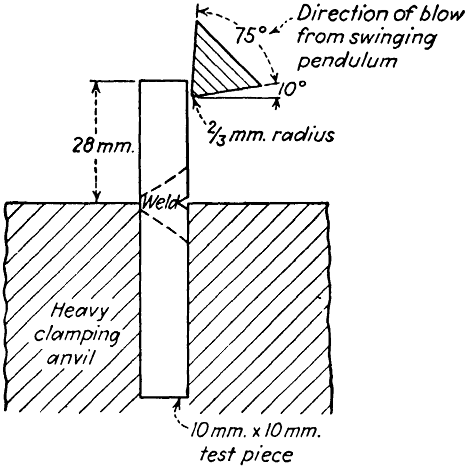

Direction of blow from swinging pendulum
75°
10°
2/3 mm. radius
28 mm.
Weld
Heavy clamping anvil
10 mm. x 10 mm. test piece

FIG. 270.—Setup for Izod test.

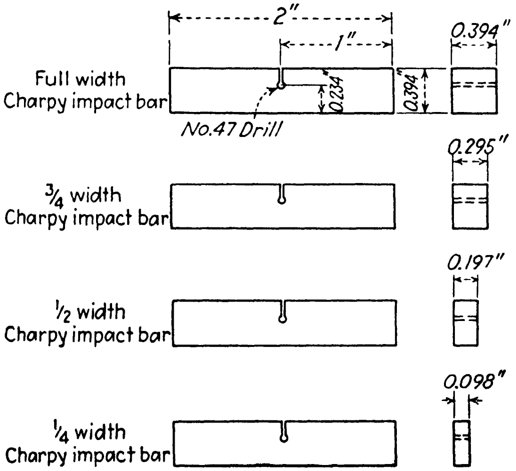

2"
1"
0.394"
Full width Charpy impact bar
0.234
0.394
No.47 Drill
0.295"
3/4 width Charpy impact bar
0.197"
1/2 width Charpy impact bar
0.098"
1/4 width Charpy impact bar

FIG. 271.—Charpy impact test specimens (keyhole notch).

In the *Izod* method, the specimen is prepared as shown in Fig. 269 and is placed and held in a viselike fixture in the Izod testing machine (see Fig. 270). A weight swings against the specimen and deforms it.

In measuring the impact strength of welds, three specimens are usually tested. In the first, the notch is placed at the bottom of the weld; in the second, the notch is placed at the side; and in the third, the notch is on top. The three results are then averaged.

In the *Charpy* machine, the swinging pendulum strikes a specimen centrally supported as a beam and having a keyhole notch. This type of notch may be obtained by drilling a hole and hack-sawing through to the hole (see Fig. 271).

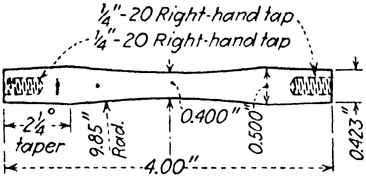


FIG. 272.—Diagram of specimen for fatigue test of weld metal.

In both the Izod and Charpy tests, the swinging pendulum is retarded when it strikes the specimen, and energy is consequently taken from the pendulum. This energy, usually expressed in foot-pounds, is measured by noting the height to which the pendulum rises after striking the specimen, as compared with the original height from which it started. From this difference and the effective weight of the pendulum, the foot-pounds of energy removed may then be calculated. Most impact-testing machines are provided with a pointer restrained by friction and so arranged that the motion of the pendulum moves it into position; it then indicates the foot-pounds directly on a suitable scale.

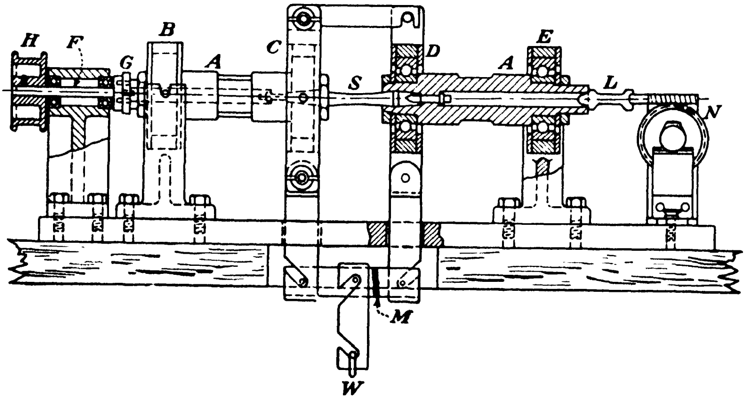


FIG. 273.—Rotating-beam fatigue testing machine.

Fatigue Test.—Several methods are used to determine the resistance of weld metals to repetition of stress or fatigue. In all methods, an attempt is made to simulate service conditions. In one, a suitably prepared specimen is bent back and forth; in another, a beam is rotated; in still another, a cantilever is rotated. In each method, a large number of definite cycles of stress is applied to the specimen, each cycle consisting of a variation from maximum tension stress value to maximum compression value, both stresses being imposed by transverse loading. The stress range is determined and the number of cycles imposed before failure is recorded. A weld-metal test specimen is shown in Fig. 272, and a fatigue-testing machine is shown in Fig. 273.

Specific-gravity Test.—The specific-gravity test, performed only in the laboratory, is carried out to make sure that no fine porosity exists. The test piece consists of a cylinder of weld metal ⅝ in. in diameter and 2 in. long (see Fig. 274). The weight and volume of the specimen are carefully determined in metric units. The specific gravity is obtained by dividing the weight, in grams, by the volume, in cubic centimeters. A specific gravity of 7.80 g. per cu. cm. is required for highest quality of weld metal. This figure is materially affected by even the smallest imperfections, such as blowholes and slag. One method of making specific-gravity tests is shown in Fig. 275.

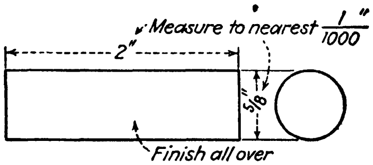


Fig. 274.—All-weld-metal specific-gravity test specimen.

Hardness Test.—Like the specific-gravity test, the hardness test is not widely used in the field but is confined mostly to the laboratory.

The Brinell and the Rockwell hardness-testing machines are the two most widely used, although the Shore scleroscope is also used. The Brinell test consists in mounting the specimen on an anvil and applying a pressure of 6,615 lb., or 3,000 kg., against a 10-mm.-diameter hardened-steel ball in contact with the specimen. The load is allowed to remain for a period of ½ min., the pressure is then released, and the diameter of the indentation in the specimen is measured. The Brinell number is computed with the aid of the following formula:

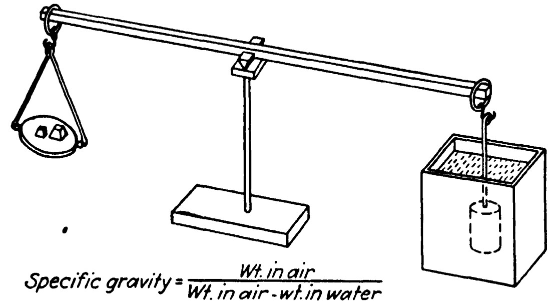


Fig. 275.—Method for making specific-gravity test.

$$\text{Brinell number} = \frac{P}{A}\sqrt[5]{D}$$

where P is the load, A is the superficial area of the depression, and D is the diameter of the ball.

Charts giving the Brinell number for any diameter indentation are available.

The Rockwell tester works practically on the same principle as the Brinell tester. It differs in that a cone-shaped diamond is used as a penetrator. The depth of the depression is measured and indicated on a dial attached to the machine.

Corrosion Test.—As far as corrosion is concerned, the most important items to consider are the parent metal and the weld metal. The weld metal deposited by shielded-arc electrodes is of a superior corrosion resistance to that deposited by bare electrodes, and this may be proved by a simple test. If two mild-steel beads, one made with bare electrodes and the other with coated electrodes, were deposited side by side on one plate and if the plate were immersed in mild acid, it would soon be noticed that the bead made with bare electrodes becomes very porous and that the shielded-arc deposit shows no corrosion (see Fig. 276).

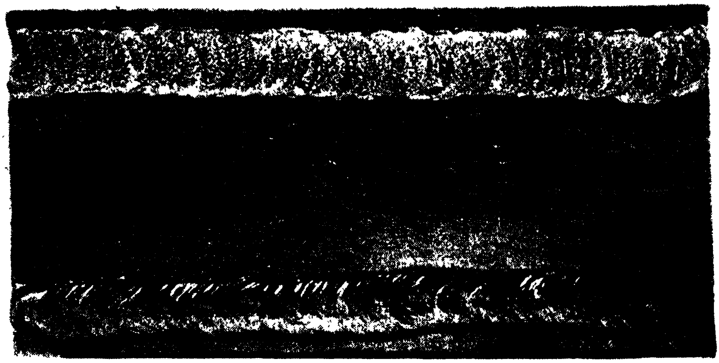


FIG. 276.—Specimen showing effects of corrosive medium on weld made with bare electrodes (upper weld), and on weld made with coated electrodes (lower weld) in mild steel plate. (*Courtesy of The Lincoln Electric Company.*)

Drift and Crush Tests.—In the testing of welded tubing of relatively small diameters, it is not always possible to obtain the specimens for tensile and bend tests. Thus, the drift and crush tests are used to test such welds (see Figs. 277 and 278).

The *drift test* consists in forcing a tapered hardened-steel drift into the end of the longitudinally welded tube. The drift may be driven by a hammer; or, better yet, it may be forced in with a press, the factor of shock being thus eliminated. The tube end is gradually expanded until it fails by splitting. Of course, if the failure occurs outside the welded area, it is positive proof that the weld is stronger than the parent metal and that it has adequate toughness and ductility. The ductility of the welded tube is measured by the distance the drift is forced into the tube. Since this test expands the welded joint, its action is much like that of the tensile test.

In the *crush test*, a short length of welded tubing is placed axially in a compression machine and loaded. The specimen collapses like a bellows and in so doing is subjected to shear, tensile, and bending stresses.

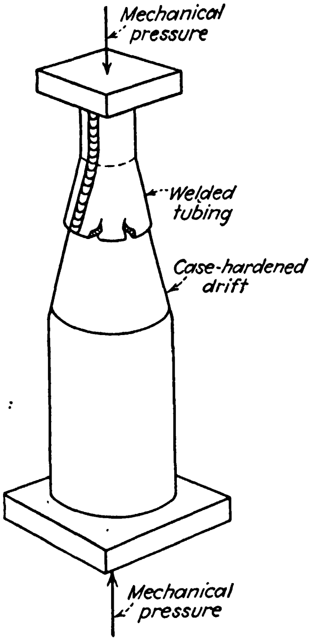


FIG. 277.—Drift test.

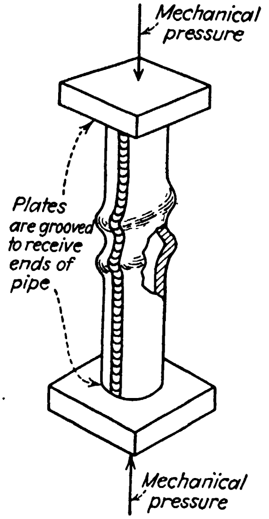


FIG. 278.—Crush test.

NONDESTRUCTIVE TESTS

Visual-examination Test.—This test, although not generally specified, is one of the simplest nondestructive tests. It consists merely in watching the progress of a welding operator while he is making a weld.

Visual inspection, though valuable in studying procedure, requires a careful observer, properly trained. The inspector observes how the filler rod or electrode melts down, notes the fusion and penetration, listens to the sound of the arc, or observes the flame adjustment of the torch. All these factors, properly studied and understood, supply invaluable information regarding the quality of the weld under observation. If the inspector cannot be present while welding is going on, he may, to a certain extent, judge the welds by their external appearance. Of course, good-looking welds are not always of the best quality, but some of the properties of a finished weld may be gauged by the appearance of weld contour, reinforcement, undercutting, overlap, and penetration.

Hydrostatic-pressure Test.—Where absolute tightness of all joints is essential, such as in tanks, closed containers, and pressure vessels of all types, the soundness of the welds may be tested by the application of internal pressure. If possible, this pressure should be hydrostatically applied, for with this method there is little tendency for parts to be violently thrown about in case of sudden release of pressure.

The equipment required for hydrostatic-pressure testing consists of pump, pressure gauge, and necessary piping connections. The vessel is completely filled with water, and all air bubbles are allowed to escape, to eliminate air pockets. After all outlets to the vessel have been closed, the pump is operated until the desired pressure is obtained (see Fig. 279). Pressures up to 6,000 lb. per sq. in. can be easily obtained.

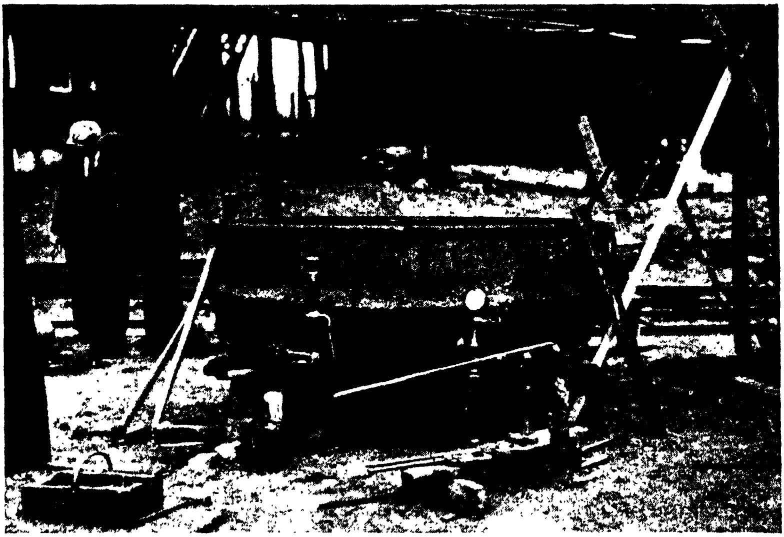


FIG. 279.—Hydraulic test of jacketed kettle. (*Courtesy of The Linde Air Products Company.*)

In the case of pressure vessels, specifications may call for a hammer test while the vessel is under a pressure of twice the determined working pressure. The weight of the hammer in pounds is equal to the shell thickness in tenths of an inch. The blows are struck at 6-in. intervals on both sides of the weld for a full length of the seam. A thorough visual inspection follows. The pressure is then raised to three times the working pressure, and the seam is again inspected.

Air-pressure Test.—In certain instances, as in the case of pipe lines for oil and gas, it may be inconvenient to use hydrostatic pressure for testing. Besides the difficulty of obtaining the required amount of water to fill the line, there is difficulty in draining out the water after the tests are completed. Therefore, an air-pressure test is used. After attaching pressure gauges, all outlets of the vessel are closed, and compressors are placed in operation until the required test pressure is built up. Each weld is then painted with soapy water and carefully inspected for bubbles which would indicate leaks. In the case of small low-pressure vessels, the entire vessel may be submerged in a large vat of water to locate any possible leaks.

But since air is compressible, testing with air pressure of any considerable amount should not be done, because of the danger involved. For instance, if a tank should be subjected to a pressure of 80 to 100 lb. and a failure should result, the air would expand with such violence that injury to someone in the vicinity would be likely to occur.

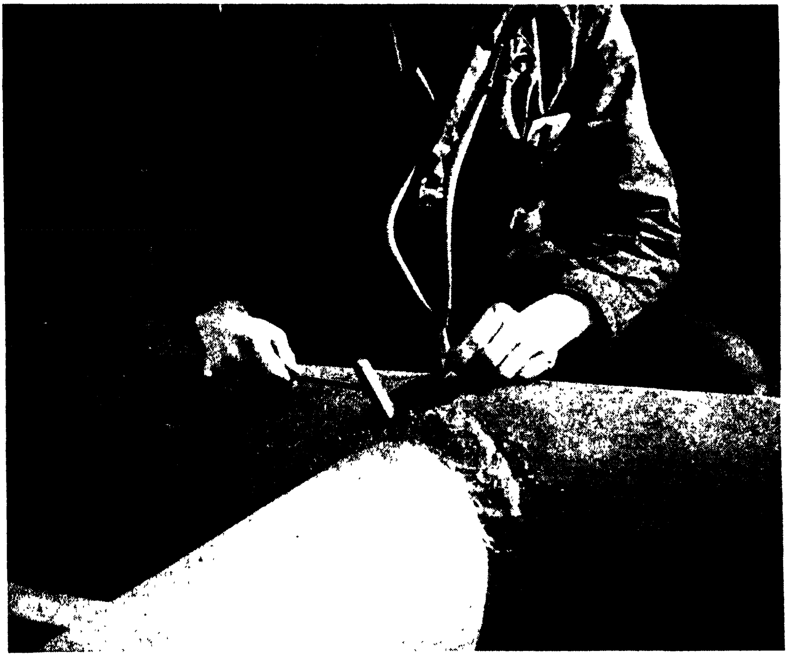


FIG. 280.—Stethoscopic test of weld. (*Courtesy of The Linde Air Products Company.*)

Stethoscopic Test.—The object of this test is to determine by means of the sound a weld gives off when tapped with a hammer whether the metal is sound or contains defects, such as lack of fusion or cracks (see Fig. 280). Sound weld metal gives a good ringing note, whereas faulty metal gives a flat note. This may be compared to the clear ringing note given off by a sound bell and the reedy note produced by a cracked bell.

In sounding certain structures, however, there are many difficulties due to the forced and natural vibration of the structure and the tendency for the natural vibration to drown out all other sounds.

An ordinary physician's stethoscope is used to magnify and identify the sound. To avoid any extraneous sounds resulting from scraping the stethoscope on the metal, the stethoscope is equipped with a gum rubber tip.

Pressure vessels, structural welds, and other types of weld have been successfully tested by means of the stethoscopic test.

X-ray Test.—The internal defects of welds may be made visible on photographic films by means of X rays. All types of cracks, slag, blowholes, lack of fusion, and so on can readily be detected. In general, the method consists in placing the X-ray tube on one side of the piece being tested and the film on the other (see Fig. 281). The time of exposure ranges from a fraction of a minute to 15 min., depending on the power of the tube and the thickness of the metal. The film is then developed and examined for defects in the weld.

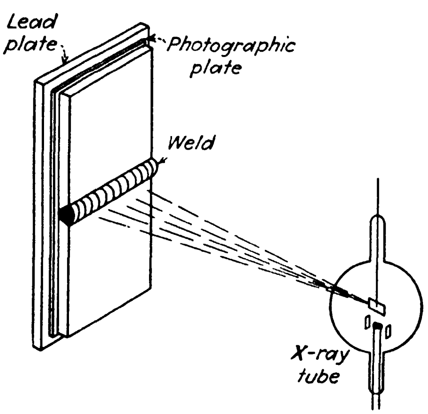


FIG. 281.—X-ray test setup.

A radiograph may be described as a shadow picture of material more or less transparent to radiation. The X rays darken the film so that regions of lower density which readily permit penetration appear dark on the negative in comparison with regions of higher density which absorb more of the radiation. Thus, the imperfections, being less dense than the base metal, will show as darkened regions on the radiograph.

The X-ray test, recognized as one of the foremost nondestructive tests, has a wide industrial use. It is required by the A.S.M.E. Code for class I welded pressure vessels.

Gamma-ray Test.--Newer than the X-ray testing, but similar in method, is the testing by gamma rays.

The gamma ray, a ray emanating from radium, has the property of penetrating metals more rapidly than the X ray. Therefore, it is more applicable to those heavy sections which would require impracticably long exposures to X rays. It is successfully used for the testing of steel plates up to 12 in. in thickness.

The limitations of the gamma-ray testing method as compared with the X-ray method of inspection are the difficulty of obtaining sharp definition of detail, the longer time required for exposure, and the difficulty of working out an exact operating technique to cover these conditions.

One actual test method might consist of arranging several large castings radially around a capsule containing radium. The films, of

course, would be placed on the side of the casting opposite from the radium.

The operator of a gamma-ray testing machine should be very familiar with the properties of radium and should be well protected from its effects.

Magnetic Test.—The magnetic test involves an examination of the effects produced by passing a magnetic flux through a weld and the adjacent base metal.

The magnetic reluctance of a weld of ferromagnetic material is increased by any fault present in it. Thus, if a magnetic flux is passed through the weld and adjacent base metal, with the lines of flux approximately at right angles to the weld, there will be more leakage flux directly over the faults than over good sections of the weld. The faults can be detected either by sifting iron filings or iron powder on a piece of paper placed on the weld and observing the picture formed or by exploring with an instrument capable of reading the strength of the leakage flux.

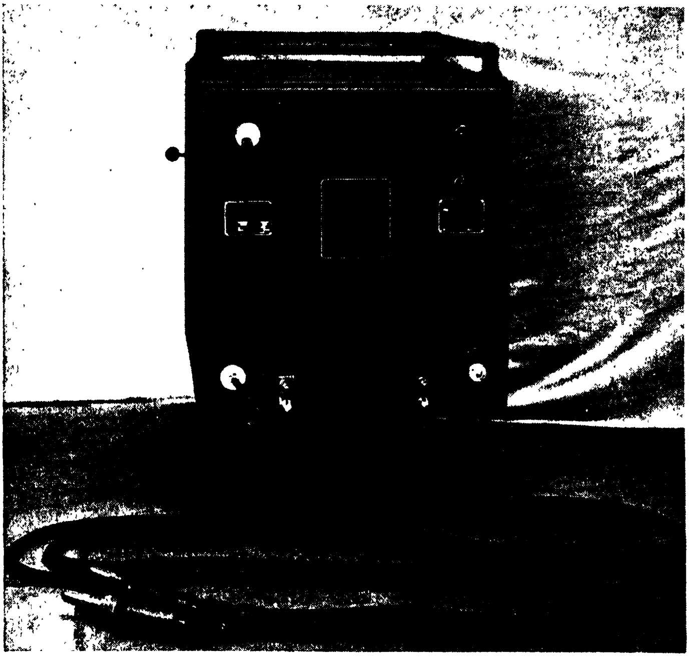


FIG. 282.—Power unit with hand-prod type contacts used for magnetic test. (*Courtesy of Magnaflux Corporation.*)

This type of test is quite sensitive to cracks or poor fusion at a short distance under the surface of the weld, especially if the weld is smooth and in flat position. If the surface of the weld is rough, sloping, or vertical or if the fault is buried far beneath the surface, the sensitivity of the weld is considerably impaired.

Fig. 283.—Cable-wrapping method of magnetic test applied to large vessel. (*Courtesy of Magnaflux Corporation.*)

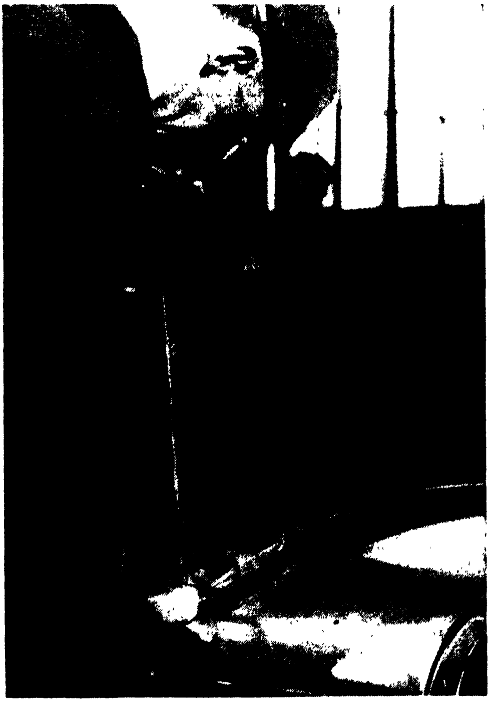


Fig. 284.—Testing by reheating welds. (*Courtesy of The Linde Air Products Company.*)

For the inspection of welded seams and other field inspections, the required magnetizing field is induced by passing high-amperage current directly through the section. For this purpose, convenient magnetic hand-prod type contacts have been developed. By means of these, copper contacts can be quickly attached magnetically to any desired points on the steel structure. A portable power unit supplies the power for both the hand-prod type contacts and the high-amperage current (see Fig. 282). The cable-wrapping method is also used for such inspections (see Fig. 283).

After inspection, demagnetization of the magnetized parts is often necessary and should be properly carried out.

Reheating of Welds.—Light-gauge sheet-metal products which cannot be subjected to pressure tests may be tested by reheating the welds with a blowpipe (see Fig. 284). By use of a fairly large head on the blowpipe, the entire length of the seam is heated gradually and evenly to a medium heat. Since the weld is thicker than the adjacent sheet metal, it does not heat up so readily as the sheet. A perfect weld will show a uniform unbroken dark strip in the heated area. The presence of any defects, such as incomplete penetration or blowholes, will be indicated by bright spots in the relatively darker weld area. Where thorough fusion has not been obtained between the base metal and the weld metal, these sections will also show up bright, whereas the rest of the weld will remain dark.

CHAPTER XV

FLAME AND ARC CUTTING OF METALS

Up to a few years ago, the shaping, finishing, or cutting of metals in general could be done only by some costly machine-shop or allied process operation. Today, the very same thing may be easily and economically done by means of a high-temperature gas flame or an electric arc.

OXYACETYLENE CUTTING[1]

Oxyacetylene cutting of ferrous metals is a process of preheating the material to be cut to its kindling or ignition temperature and rapidly oxidizing it by means of a closely regulated jet or stream of oxygen issued from a special tool called a "cutting blowpipe" or "cutting torch." Hence, it is primarily a chemical process based on the remarkable chemical affinity of oxygen for ferrous metals when raised to or above the kindling temperature.

When commercially pure oxygen is brought into contact with most steels or iron, at kindling point, a very active chemical reaction between them results. In the case of plain carbon steel, the metal is preheated to a bright-red color, in daylight, reached between 1400 and 1600°F., approximately. The gases supplied and the rate of progression of the cutting should be closely regulated for accurate control.

Only the metal within the direct path is acted upon, to form a narrow race, or "kerf," as it is usually called, having uniformly smooth and parallel walls. Under skilled workmanship, with mechanically guided cutting torches or blowpipes, cutting tolerances as to squareness and longitudinal alignment of the cut may be held within close limits.

The faces or walls of the cut or race, in the commonly used steels, are not injured by the cutting operation. On the contrary, their strength and toughness, if of plain low-carbon steel, are slightly improved, as explained in the section devoted to the effect of cutting on steel. The heat effect upon the metal induced by normal cutting operations penetrates about $1/10$ in. below the cut surface.

In addition to the chemical reaction, there is a noticeable and very helpful mechanical eroding effect produced by the kinetic energy or motive power of the cutting oxygen stream which washes away some of the metal in unconsumed or metallic form.

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[1] Much of the material in this section has been condensed from literature issued by the I. A. A.

With the oxyacetylene cutting process, heavy cuts can be made practically as cheaply as cuts made in lighter gauges. Heavy sections, heretofore uneconomical to cut by any mechanical cutting process, are readily and smoothly cut with oxygen.

In addition to linear gas cutting, several other types of controlled oxidation are in use. One application, known generally an "oxygen lance cutting," employs a relatively long section of small-diameter iron pipe. The end of the pipe is ignited and maintained so by a stream of oxygen flowing within the pipe. This furnishes preheat as well as free oxygen for cutting, forming a lancelike cutting tool which is used primarily for emergency and heavy-duty cutting.

FIG. 285.—Shaping of large steel section on location by means of oxyacetylene cutting. (*Courtesy of The Linde Air Products Company.*)

Another application is that known as "flame machining." This process of cutting is used primarily to surface ferrous metals in much the same way as a planer or milling machine does. The cut does not penetrate through the work, as in linear gas cutting.

Since the oxyacetylene-cutting apparatus is, in general, easily portable, it can readily be taken to the work. This reduces to a minimum the handling of unwieldy objects to be cut.

Chemistry of Oxyacetylene Cutting. *Oxidation of Ferrous Metals.*—The iron oxide formed in gas cutting is a black, brittle, magnetic iron oxide. Its chemical formula is Fe_3O_4. It contains a smaller proportion of oxygen than rust or red iron oxide, Fe_2O_3. The complete equation for the oxidation reaction in gas cutting is

$$\underset{\text{Iron}}{3Fe} + \underset{\text{oxygen}}{2O_2} = \underset{\text{black iron oxide}}{Fe_3O_4} + 26{,}691 \text{ cal.}$$

Three atoms of iron, Fe, combine with two molecules of oxygen, O_2, to produce one molecule of black iron oxide, Fe_3O_4. In this oxidation reaction, 1,593 cal. per g., or 2,870 B.t.u. per lb., of iron are produced. This represents the calorific energy of the oxidation of iron.

The atomic weight or iron, Fe, is 55.84, and the molecular weight of oxygen, O_2, is 32. Therefore, the relative weights of the iron and the oxygen in magnetite, Fe_3O_4, are as 167.52 is to 64.00, or as 2.618 is to 1. It follows that 1 lb. of oxygen will oxidize 2.618 lb. of pure iron to magnetite, Fe_3O_4. Now, oxygen at 70°F. and 1 atm. pressure has a volume of 12.07 cu. ft. per lb., and pure iron weighs 0.285 lb. per cu. in. The theoretical data given below have been computed from these constants.

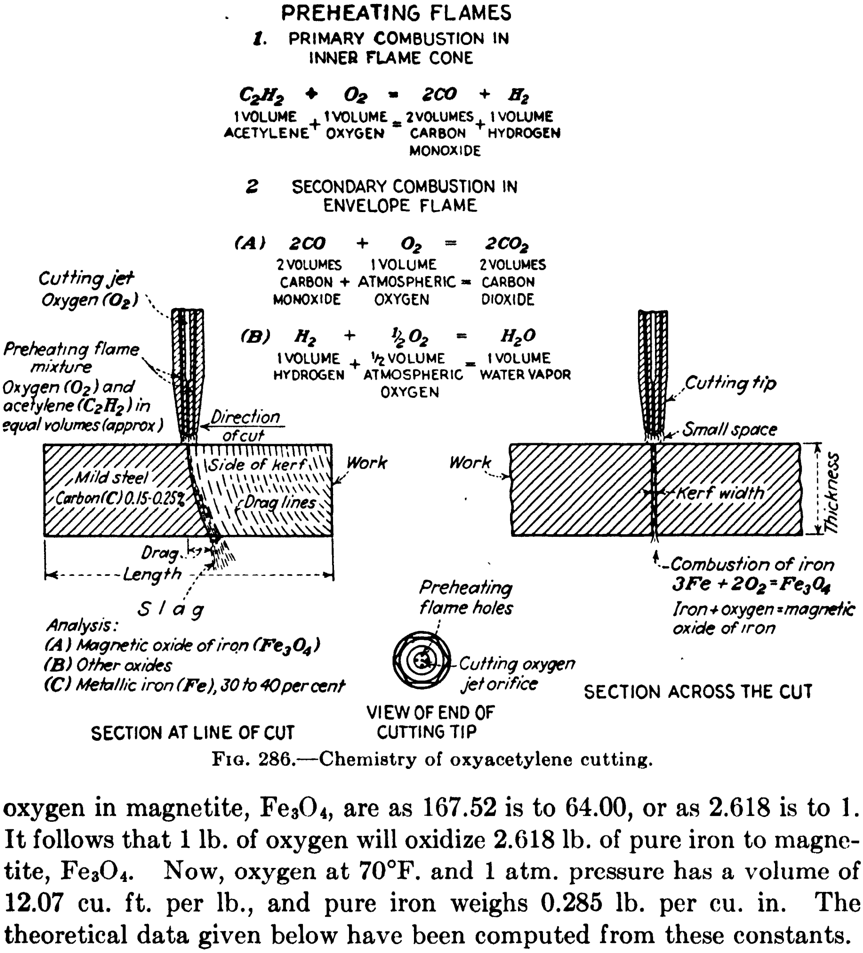

PREHEATING FLAMES
1. PRIMARY COMBUSTION IN INNER FLAME CONE
$C_2H_2 + O_2 = 2CO + H_2$
1 VOLUME ACETYLENE + 1 VOLUME OXYGEN = 2 VOLUMES CARBON MONOXIDE + 1 VOLUME HYDROGEN
2 SECONDARY COMBUSTION IN ENVELOPE FLAME
(A) $2CO + O_2 = 2CO_2$
2 VOLUMES CARBON MONOXIDE + 1 VOLUME ATMOSPHERIC OXYGEN = 2 VOLUMES CARBON DIOXIDE
(B) $H_2 + \frac{1}{2}O_2 = H_2O$
1 VOLUME HYDROGEN + ½ VOLUME ATMOSPHERIC OXYGEN = 1 VOLUME WATER VAPOR
Cutting jet Oxygen (O_2)
Preheating flame mixture Oxygen (O_2) and acetylene (C_2H_2) in equal volumes (approx)
Direction of cut
Side of kerf
Work
Mild steel Carbon (C) 0.15-0.25%
Drag lines
Drag
Length
Slag
Analysis:
(A) Magnetic oxide of iron (Fe_3O_4)
(B) Other oxides
(C) Metallic iron (Fe), 30 to 40 per cent
SECTION AT LINE OF CUT
Preheating flame holes
Cutting oxygen jet orifice
VIEW OF END OF CUTTING TIP
Cutting tip
Small space
Work
Kerf width
Thickness
Combustion of iron $3Fe + 2O_2 = Fe_3O_4$
Iron + oxygen = magnetic oxide of iron
SECTION ACROSS THE CUT

FIG. 286.—Chemistry of oxyacetylene cutting.

1 lb. oxygen will oxidize 2.618 lb., or 9.186 cu. in., of pure iron.
1 cu. ft. oxygen will oxidize 0.217 lb., or 0.761 cu. in., of pure iron.
1 lb. of pure iron requires for oxidation 0.382 lb., or 4.610 cu. ft., of oxygen.
1 cu. in. of pure iron requires for oxidation 0.109 lb., or 1.314 cu. ft., of oxygen.

As already mentioned, the iron removed from the kerf in actual gas cutting is not entirely consumed by the oxygen. Owing to the eroding effect of the cutting oxygen jet or stream, about 30 to 40 per cent of the metal is washed out of the cut as unconsumed or metallic iron. Because of this fortunate circumstance, it is not uncommon to obtain satisfactory cuts with a cutting oxygen consumption of 1 cu. ft. of oxygen per cubic inch of material removed from the kerf, or even less. This, as may be seen from the above data, is more than 30 per cent better than the theoretical figures for the oxidation, which are based on chemical reaction alone and make no allowance for the mechanical eroding effect of the cutting oxygen jet in washing out molten iron in unoxidized form.

Ordinary steels contain carbon, manganese, silicon, and other elements in combined form, but in such minute proportions as to have little or no influence on the oxidation of the metal in gas cutting. However, certain alloy steels contain chromium, nickel, and other elements in sufficient amounts to have a marked retarding effect on the oxidation reaction. The uncombined or graphitic carbon in cast iron has a similar influence. Such materials are harder to cut and require special techniques.

Combustion of Acetylene.—Acetylene, C_2H_2, is an unsaturated hydrocarbon gas; when it burns, it gives off carbon dioxide, CO_2, and water vapor, H_2O, as products of complete combustion and liberates heat. The oxidation reaction for acetylene is as follows:

$$\underset{\text{Acetylene}}{C_2H_2} + \underset{\text{oxygen}}{2\tfrac{1}{2}O_2} = \underset{\text{carbon dioxide}}{2CO_2} + \underset{\text{water vapor}}{H_2O} + 542{,}700 \text{ B.t.u.}$$

That is, 1 molecule of acetylene unites with $2\frac{1}{2}$ molecules of oxygen to form 2 molecules of carbon dioxide and 1 molecule of water vapor, with a liberation of 542,700 B.t.u. of heat.

Most hydrocarbons are exothermic, generating heat during formation and absorbing the same amount of heat during combustion. But acetylene is highly endothermic, absorbing heat during formation and liberating it again on burning or decomposing. The endothermic heat liberated by acetylene is in addition to that produced by the combustion of its component elements. The total heat generated is given in Table XXI.

TABLE XXI.—HEAT PRODUCED BY COMPLETE COMBUSTION OF ACETYLENE

Name of constituent	Reaction formula	B.t.u. per mole	B.t.u. per cu. ft. at 60°F. and 1 atm.	Per cent of total
Endothermic	$C_2H_2 = 2C = H_2$	86,600	228	15.9
Carbon	$2C + 2O_2 = 2CO_2$	352,000	928	64.8
Hydrogen	$H_2 + \frac{1}{2}O_2 = H_2O$	104,100	277	19.3
Total heat of combustion		542,700	1,433	100.00

Acetylene contains the highest percentage of carbon (92.3 per cent of weight) of any common gaseous hydrocarbon compound. This coupled with its exceptionally large endothermic heat gives it the highest flame temperature, by a wide margin, of any known fuel gas (see Table XXV).

Oxygen Purity.—High-purity oxygen is essential for rapid and efficient cutting. Purity of 99.5 per cent or better has been standardized by the suppliers of oxygen for welding and cutting. Purities below this figure operate to lower materially the efficiency and economy of cutting.

Effect of Cutting on Steel.—When steel of ordinary temperature is cut with the oxyacetylene torch, the metal next to the cut face is heated red hot to a depth of a few hundredths of an inch. This red-hot metal is cooled quickly on account of conduction of the heat into the adjoining cold metal. The nature and arrangement of the constituents of the steel and its physical properties are affected by the rate of cooling from the high temperature. If cooling is very rapid, the steel becomes extremely hard and brittle. With slightly less rapid cooling, the steel has greater strength and toughness. If the cooling is still slower, a fully annealed structure is obtained. The property of hardening and/or strengthening depends not only upon the rate of cooling from a high temperature but also upon the content of carbon in the steel and various other elements such as chromium, vanadium, and tungsten.

In cutting at an angle to provide a bevel, the heat effect upon the surface cut is slightly different from that where the cut is made at a 90-deg. angle in the same part. Beveled cuts, owing to their longer length through the part, are made at a slower cutting rate, and therefore the preheating flames play at a longer interval of time upon the point along the line of cut. Also, the sharpness of the corner of the cut along its bottom edge tends to absorb more of the cutting heat than an abrupt square edge does. In addition, there is more time and opportunity for the heat from the slag produced by the cutting operation, all of which passes the bottom edge of the cut, to penetrate the metal along the bottom edge. These conditions operate to increase the depth of the heat-affected zone at the cut ends. Nominally, these regions of the heat-affected zone are twice the depth of the heat-affected zones of ordinary 90-deg. cutting, or in the neighborhood of $\frac{1}{8}$ to $\frac{1}{5}$ in.

Where the cut surfaces are welded later, the welding operation acts to anneal them; in fact, it obliterates whatever change the preceding cutting may have produced in and adjacent to the cut surface.

Preheating and Postannealing.—When higher carbon steels or alloy steels are cut, they may not be ductile enough to withstand the stresses set up. It has been found by experience that if these steels are preheated to a temperature of about 500 to 600°F., possible cracking will be avoided.

Since steel oxidizes more easily at elevated temperatures, the expense that accompanies preheating is partly compensated for by the more rapid rate at which preheated steel can be cut. What is more, this added expense is insignificant compared with the advantage of being able to cut accurately and to shape these high-strength steels by a flame-cutting process.

When preheating has been used before cutting, there is seldom need for annealing or normalizing after cutting, for the structure set up in the steel at the cut edge is such as to give it desirable physical properties.

Warping.—To prevent warping due to local heating: (1) The cross-sectional engineering properties should be sufficient to resist the forces that such local heat sets up. (2) The part should be affixed in position by clamps or weights during the cutting operation and the subsequent cooling of the part to room temperature. (3) The cutting should be performed simultaneously or in rapid succession about the neutral axis of the part, the forces about this axis being thus equalized.

Experience has shown that above ½ in. thickness there is little tendency of a part to warp if not unduly narrow. The simple operations, such as cutting off rods or bars, structural shapes, rail, piping, and similar lengthy materials, do not involve the matter of warpage.

Account must be taken at times of the dimensional changes that are produced by the heat of cutting where great accuracy is demanded in over-all dimensions of the cut part. The intense heat along the line of cut develops expansion immediately ahead and astern of the point of cutting especially astern; upon cooling to room temperature the surface will shrink slightly, the over-all dimensions are thus affected unless a correction factor has been applied in making the cutting layout.

Oxyacetylene-cutting Equipment.—Oxyacetylene-cutting equipment consists ordinarily of the cutting torch with separable cutting tips, oxygen and acetylene hose with connections, oxygen and acetylene pressure regulators, and gas cylinders. Pressure regulators are usually equipped with cylinder and working pressure gauges. Cutting-oxygen pressure regulators are specially designed to deliver oxygen in large volumes and at higher pressures and, as a rule, are fitted with 400 lb. per sq. in. working pressure gauges. Where larger quantities of oxygen and acetylene are required, oxygen cylinders are often manifolded and acetylene generators rather than cylinders are used. For such installations, distribution pipe lines are often employed to carry both gases to the various points of consumption throughout the premises. In the case of machine flame cutting, the torch is held and operated mechanically, but its essential features remain unchanged. To assure efficient results, the manufacturer's instructions for setting up and operating the equipment should be followed closely in each case.

Oxyacetylene-cutting Processes. *Flame Cutting.*—The primary use for oxyacetylene cutting is that of severing. With this process, the cut is made through the material as at *a*, Fig. 288, the edges being left in a plane at 90 deg. to the surface of the part cut. A cutting tip or nozzle with a comparatively small-diameter straight-sided high-stream velocity type of cutting-oxygen orifice is employed. The cutting tip is preferably held perpendicular to the surface, as shown, although in certain cases it may be tilted somewhat along the line of cut. For bevel cutting, the tip is tilted sidewise to the required angle, but the cut still penetrates through the material. These processes are widely known as "flame cutting."

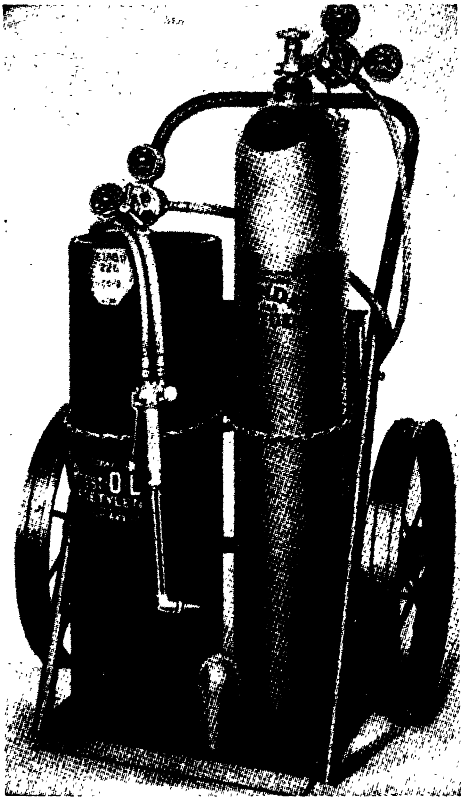


FIG. 287.—Oxyacetylene hand cutting equipment. (*Courtesy of The Linde Air Products Company.*)

Flame Machining.—Recently, another oxyacetylene-cutting process has begun to take shape, as a sequel to the former. It utilizes the same fundamental principle of chemical reaction but differs in that the cutting oxygen stream impinges at a more or less acute angle on the work, as at *b*, Fig. 288, in some cases almost tangentially. The cutting oxygen orifices used are of the expanding low-stream velocity type, with a comparatively large diameter at the exits. Relatively low oxygen pressures are used. The cut is not permitted to penetrate through the work, as in severing, but is restricted to removal of a predetermined depth and width of material from the surface oxidation, as indicated.

This change in the angle of impingement of the cutting oxygen stream has opened up an entirely new range of oxyacetylene-cutting operations. Because of their similarity to many operations of customary tool machining, these new operations are collectively termed "flame machining," to differentiate them from "flame cutting."

Classification of Cutting Processes.—Figure 289 is a classification chart of oxyacetylene cutting processes listing the various operations now in commercial use and under development.

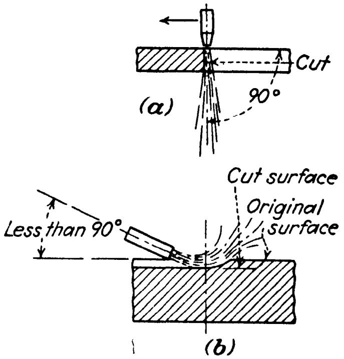


FIG. 288.—A change in the position of the cutting flame opens a new field of application.

General Principles of Flame Cutting.—Certain general principles are common to all flame cutting, whether performed by hand or machine. The more important of these will be discussed briefly before individual flame-cutting processes, to which they also apply, are taken up.

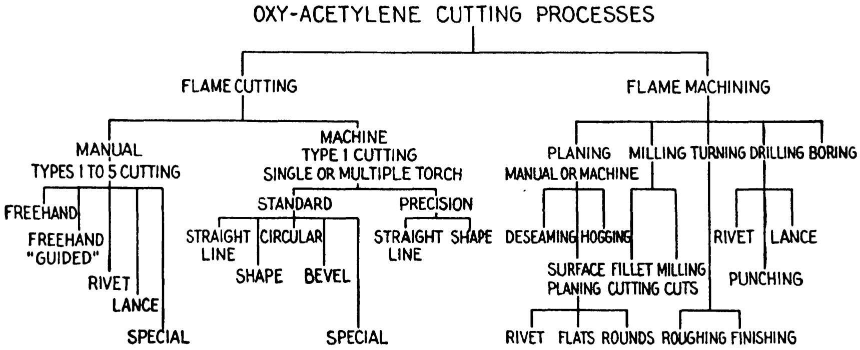


FIG. 289.—Classification of oxyacetylene cutting processes.

Drag and Quality.—For flame cutting, the cutting oxygen jet on entering the cut is usually in line with the cutting oxygen orifice axis (*a*, Fig. 288). After traversing about one-half the thickness of the cut, however, it may curve backward in a direction opposite to the travel (see Fig. 286). When this occurs, the amount by which the oxygen jet falls behind the perpendicular in passing through the material is known as the "drag" of the cut. Faint markings called "drag lines" left on the face of the cut enable this to be measured, as shown in Fig. 286. In heavy cuts, these markings are more pronounced. Cuts with short or negligible drags are known as "high-quality cuts," and those with long drags are known as "low-quality" cuts.

Cutting studies have revealed the following facts: (1) As the drag is increased, the oxygen consumption is increased. For very short drags, a slight decrease in drag length can be procured at the expense of increased oxygen consumption. (2) Except for low cutting speeds, a certain minimum length of drag is characteristic of a given tip and speed regardless of the operating pressure (or the oxygen consumption). (3) An increased drag may result if an attempt is made to obtain a drag shorter than the minimum by increasing the operating pressure beyond that at which the minimum drag is obtained.

In considering the economies of flame cutting, therefore, it is essential to determine how short the drag must be to fulfill the requirements. If it is too long, an uncut final corner will result; and this is usually not permissible. Straight-line cuts frequently may be made with considerable drag, without much detrimental effect, for the drag lines lie within the plane of the cut and do not prevent both top and bottom edges of the cut from being left clean and sharp. This procedure saves considerable oxygen. It is also applied in scrap cutting, where cut quality is nonessential, so long as severing is accomplished. However, in shape cutting, in rounding curves or corners, less drag is permissible, for the bottom contour of the cut will tend to come out differently from the top with the edges not square. Such cuts must be made of small drag of high quality. They require a good deal more oxygen than cuts with long drags which barely penetrate the material. Precision-machine flame cuts are necessarily of high quality.

Satisfactory Commercial Flame Cuts.—Satisfactory cuts must have a drag sufficiently short for the purpose intended and to allow cutting the final corner and "dropping" the piece. The sides of the cut should be sufficiently smooth—not grooved, fluted, or ragged. The slag condition on the bottom of the cut should be satisfactory; that is, for most production work there should be no firmly adhering slag that involves an appreciable expenditure of labor for its removal. Only loose slag or none at all is preferable; this is quite readily attained under proper conditions of cutting. Finally, the upper edges of the cut should be sufficiently sharp to meet the requirements of the particular job.

The following conditions are necessary to obtain smooth cuts: (1) suitable cutting tip, with correct-size cutting orifice and proper degree of preheat; (2) proper oxygen and fuel gas pressures; (3) correct cutting speed; (4) uniformity of torch movement; (5) uniform oxygen and fuel-gas pressure regulation; (6) smooth and uniform bore and proper type of cutting orifice; (7) cleanliness of orifice exit; (8) cleanliness of preheat holes (end of tip must be kept free from adhering slag); (9) high-purity oxygen; (10) proper angle of incidence of the cutting oxygen stream to the upper edge.

Selection of Cutting Tip.—A wide variety of cutting tips of different styles and sizes is available for flame cutting. They provide for cutting various thicknesses of most ferrous materials and for different surface conditions, such as clean, painted, rusty, or scaly surfaces. Theoretically, the heat generated by the combustion of the material in cutting should be sufficient to make the adjacent metal red-hot, so that, once started, the cut might be continued indefinitely with oxygen only. Practically, the smoothness of this theoretical operation is disturbed by heat conductance of the material, radiation losses, and dirt, rust, paint, or scale on the surface, so that preheating flames are essential, not only to start the cut but to carry it on uninterruptedly. In flame cutting, the selection of the tip having the correct diameter of cutting oxygen orifice is determined primarily by the thickness of the material to be cut. Surface conditions and chemical composition of the material are the most important considerations in selecting a cutting tip with the right intensity of preheating flames. Very rusty or scaly surfaces are often cleaned along the line of cut before cutting, either by cracking the scale loose with the torch preheating flames or mechanically with scrapers or chipping hammers.

Economic Factors.—The use of oversize cutting tips and excessive oxygen and acetylene pressures for the work in hand causes gases to be wasted. A cutting tip with a large cutting oxygen orifice necessarily cuts a wider kerf and consumes more oxygen than a tip with a smaller orifice, even if lower oxygen pressure is employed. Cutting oxygen pressure of itself avails little beyond forcing sufficient oxygen into the cut to oxidize the metal in its path and blow away the resulting oxide, whereas excessive pressure causes the cutting oxygen jet to swirl and spread out after leaving the tip, a wider kerf with uneven sides and increasing oxygen consumption being thus produced. For maximum efficiency, cutting tips should be operated at, or near to, normal capacity, but not beyond. This includes normal gas pressures and cutting speeds that utilize the cutting oxygen jet to best advantage for producing the quality of cut desired. Cutting tips should, as a rule, be positioned to have one preheating hole in line with the cut, leading the cutting oxygen jet. Where preheating flames straddle the kerf with no flame directly leading the cutting oxygen jet, there is a tendency for a wider kerf with slightly rounded top edges to develop.

Starting Flame Cuts.—As a rule, flame cuts are started at the edge of the piece. The cutting torch is held so that the ends of the preheating flame cones are about $\frac{1}{16}$ in. above the surface of the material. When a spot of metal at the top of the edge has been heated to a bright red, the cutting oxygen jet is turned on. The metal in the immediate path of the cutting jet oxidizes; and as the torch is moved slowly and steadily along the line to be cut, separation is effected. In flame-cutting ordinary steel, the tip should be held vertically at an even distance above the surface and advanced uniformly at the right speed without wavering.

Piercing Holes.—In starting a flame cut in the metal away from the edge or in piercing a hole, more time is usually consumed in bringing the spot to the kindling temperature than with edge starting. When a spot is heated to a bright red, the torch is raised about ½ in. above the normal position for line cutting and the cutting oxygen turned on slowly. As soon as the plate is perforated, the torch is lowered to the normal height above the work, and any further cutting that may be required is carried on. Drilled holes are used in certain cases, particularly to form a straight, smooth starting edge for a heavy internal cut.

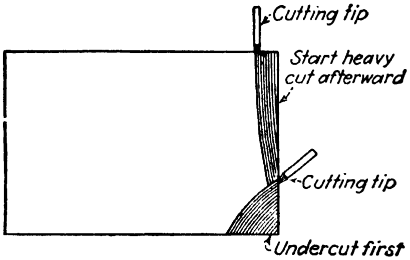


FIG. 290.—Starting of heavy cuts aided by preliminary undercutting.

Cutting Rounds.—When cutting around bar steel, pressures are set for the maximum thickness, or diameter, and the cut is started at the side. As the cut progresses, the torch is lifted to follow the circular shape. Starting is facilitated by nicking the round with a chisel to raise a burr at the point where the cut is to begin.

Heavy Cutting.—In making heavy cuts, the greatest care must be exercised in selecting the proper operating pressure. The range of suitable pressures is considerably narrower for the heavier cuts; and, at the same time, the pressure drop through the hose-line connections and the torch becomes rapidly larger with the increasingly greater oxygen flows demanded for heavy cutting. Variations in the quality of the steel are also more important.

In starting a heavy cut, considerable skill must sometimes be exercised to sever the initial lower corner completely and avoid pocketing of the cutting oxygen stream in the lower portion of the cut. The front edge of the cut should be very clean, particularly the lower portion of the front face. The axis of the tip should be aligned with the front edge of the material by turning on the cutting oxygen stream with preheating flames burning to render it visible. Upon starting the cut, the torch should be moved so that it is retarded just long enough to allow the cutting stream actively to attack the material throughout almost its entire depth. The torch is then permitted to proceed normally. In the case of very heavy pieces, the lower portion of the front face is sometimes heated with a large welding flame. In certain instances, starting is facilitated by first undercutting the forward edge of the material with a hand cutting torch (see Fig. 290). However, poor and ragged cuts may be obtained by this method unless carried out by an experienced operator.

Scope of Flame Cutting. *Limit of Thickness.*—A brief summary of the present range or scope of flame cutting will serve to explain its wide employment in industry. With regard to depths or thickness that can be flame-cut, there appears to be practically no limit. At least, the limit has not as yet been approached. Thicknesses up to 8 ft. have been successfully severed by various means, at times requiring special equipment. With standard cutting torches, not assisted by oxygen lances, to be described later, present-day limits of penetration are about 24 in. for manual cuts and 33 in. for machine cuts. Thicker sections have been cut by making a nonpenetrating cut in one side and then turning the block over and making a second cut to join the first. Particularly for freehand flame cutting, the limit depends largely upon the skill and steadiness of the operator.

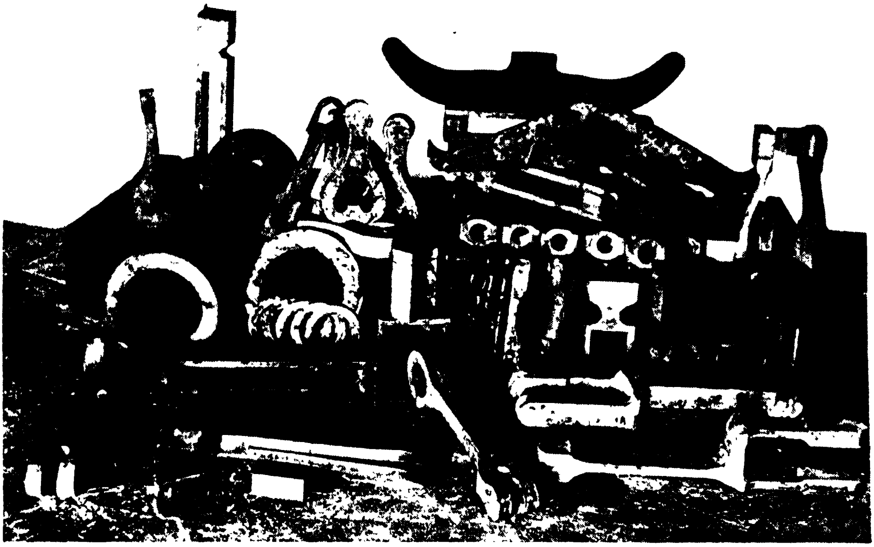


FIG. 291.—Complex shapes cut by oxyacetylene process. (*Courtesy of Air Reduction Sales Company.*)

Materials.—Almost any ferrous materials can be cut by the oxyacetylene process. However, considerable resistance is offered to the process by certain highly alloyed steels. The uncombined carbon in cast iron has a similar effect. For such materials, it is necessary to employ special flame-cutting techniques, as described later. By means of oxygen lances, practically any material, ferrous or otherwise, may be penetrated.

Crosscut Tolerances.—Where the torch is firmly held and advanced at uniform speed, as in machine flame cutting, and tolerances can be kept within very narrow limits for precision cutting, machine flame cuts are frequently so smooth and square and have such sharp edges that it is difficult at times for those not familiar with the process to credit it with such high-quality workmanship.

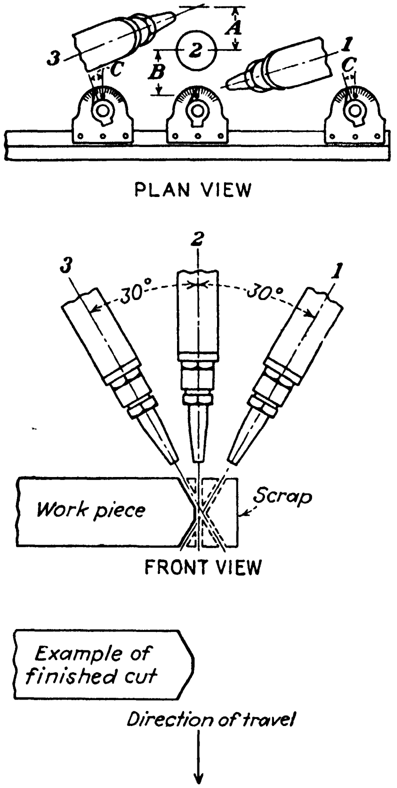


FIG. 292.—Schematic layout of torches for cutting a double bevel.

Stack Flame Cutting.—In addition to cuts made through a single thickness of material, flame cutting is utilized in some cases for cutting through several thicknesses simultaneously. This operation is known as "stack flame cutting." Though not widely applied at the present time, it may be utilized with success and economy under certain conditions of material, thickness, assembly, cut quality and tolerances, and cost of setting up the work. The plates in the stack should be clean and flat, with edges in alignment where the cut is started. Their number should vary with the thickness of individual plates, to keep stack thickness constant. They should be clamped together as nearly as possible along the line of cut. In stack flame cutting very thin plates, a "waster plate" having sufficient rigidity to lie flat while the cut is being made is usually clamped on to prevent the top thin plate from buckling. It serves also to maintain ignition in the cut by its own combustion, the speed of cutting being thus facilitated in this kind of work.

Complex Shapes.—Straight lines, circles, or irregular contours of the utmost complexity are flame-cut with equal ease, by either mechanical or hand-guide torches. Thus, it is seen that flame cutting has almost unlimited flexibility, in contrast with most machine tools.

Beveled Edges.—Angular or bevel flame cuts are made by inclining the tip and torch sideways to the desired angle or by using a bent tip.

Such cuts may be made either by hand or by cutting machines, both in straight or irregular lines and with the same depth range as in normal right-angle cutting. Beveled edges are widely used to prepare plates for welding, for mitering purposes, and to modify sharp corners.

Multiple Flame Cutting.—In many applications of machine flame cutting, a number of torches are used to cut a like number of identical shapes simultaneously. Concentric circles for flanges and the like are often cut in one operation, with two or more torches.

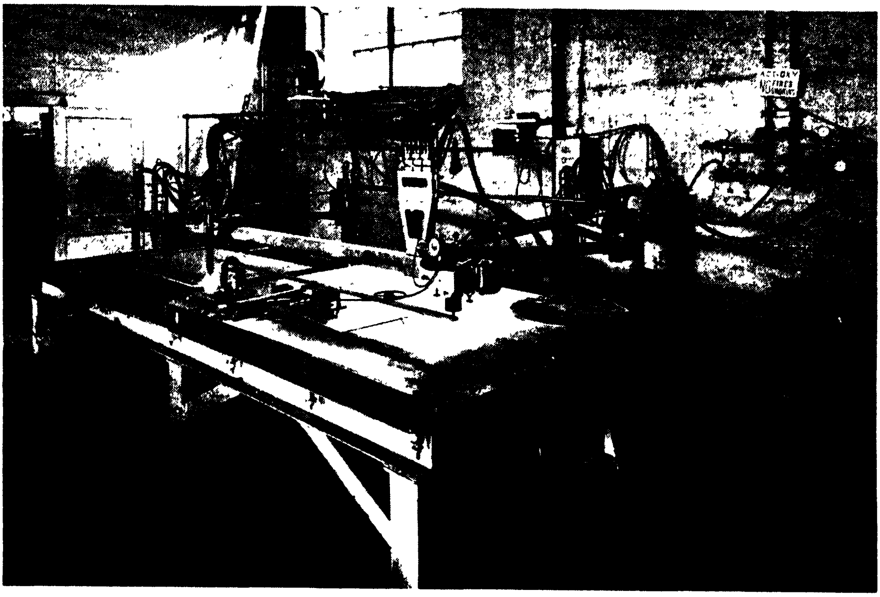


FIG. 293.—Setup for multiflame cutting. (*Courtesy of Air Reduction Sales Company.*)

Flame-cutting Techniques.—Several different flame-cutting techniques have been developed, for performing various cutting operations and for cutting different grades of ferrous metals. However, the International Acetylene Association has defined five distinct flame-cutting techniques. These are classified according to the flame movement, as shown in Fig. 294.

Type 1 *Flame Cutting.*—Type 1 is the form of flame cutting common to the plain carbon steels, whose cutting by any of the oxyacetylene processes is, generally speaking, the most autogenous of all the cuttable metals; that is, the cut is produced largely by chemical means (combustion). Once started, it proceeds freely and regularly in a line and at the will of the operator. The technique consists in first preheating a small area about the origin of the cut, until it attains a kindling temperature with oxygen (between 1400 to 1600°F.). This preheating is accomplished by means of several small oxyacetylene flames arranged around the cutting oxygen orifice. When the kindling temperature is attained, combustion of the base metal with the cutting oxygen can proceed.

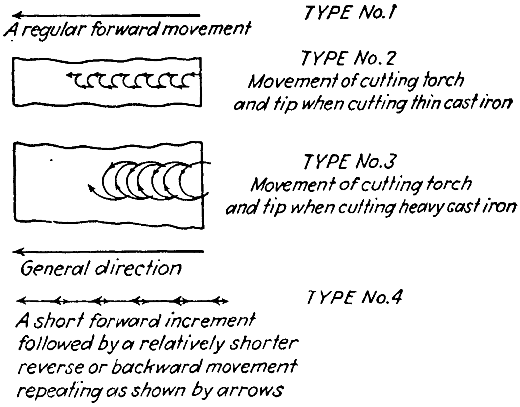

TYPE No.1
A regular forward movement
TYPE No.2
Movement of cutting torch and tip when cutting thin cast iron
TYPE No.3
Movement of cutting torch and tip when cutting heavy cast iron
General direction
TYPE No.4
A short forward increment followed by a relatively shorter reverse or backward movement repeating as shown by arrows

FIG. 294.– Types of cutting techniques.

Although, theoretically, preheating should not be necessary except for starting the cut, in practice it is maintained throughout the cutting operation, an expedient that ensures continuous cutting and high cutting speed.

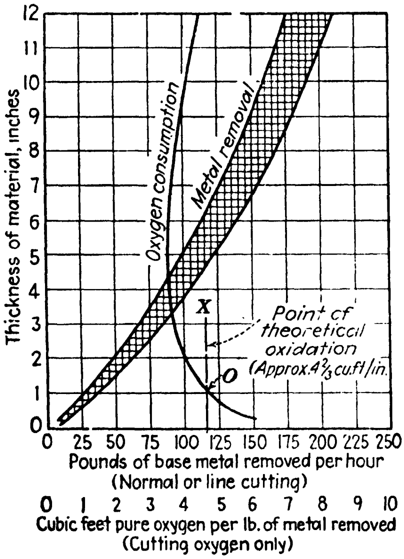


FIG. 295.—Cutting rate expressed in pounds of metal removed per unit of time.

The manipulation of the torch consists merely in holding it at the correct height above the surface and advancing it at the proper uniform speed along the line of cut. The high velocity of the cutting oxygen stream confines it to a narrow path and holds its oxidizing action to within close limits, accurate control thus being made possible. In practice, especially on heavier cuts, a considerable portion of the metal removed from the kerf is blown out in molten metallic form, without having been oxidized. The relationship among thickness, metal removed, and oxygen consumed in type 1 flame cutting is shown in Fig. 295.

Type 2 Flame Cutting.—This type of cutting is known commercially as "oxygen-lance cutting." From the standpoint of application, practically all ferrous metals and many other materials can be cut or pierced with the oxygen lance.

The lance ordinarily consists simply of a length of ¼- or ⅜-in. I.D. size black-iron pipe with a globe valve on one end, connected to an oxygen hose, regulator, and cylinder or manifold, so that only oxygen flows through the lance pipe.

Like type 1 flame cutting, a spot is first preheated to kindling temperature, usually with a welding torch with large tip. Then the end of the lance is brought against the heated area, and oxygen at about 40 to 50 lb. per sq. in. is turned on. This oxidizes the metal; and sufficient heat is produced to continue the cut or hole with oxygen alone, without any oxyacetylene flame to facilitate the progress. The end of the lance is held in the cut or hole, so that the cutting oxygen stream emerges at the point of cutting or oxidation. This heats and burns the end of the pipe. Thus, as the operation proceeds, the lance is consumed but is ultimately replaced by a new length of iron pipe. Only a small portion of the oxygen consumed is required by the oxidation of the lance itself, but the heat of the burning lance assists the cutting.

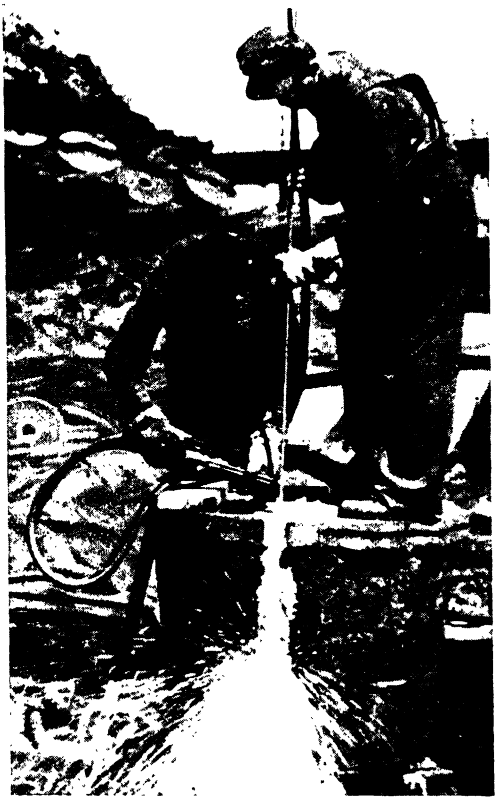


FIG. 296.—Oxygen-lance cutting. (*Courtesy of The Linde Air Products Company.*)

Once started, the reaction is very vigorous and may be increased, if desired, by using a lance pipe of greater wall thickness or by inserting one or more steel rods in the pipe. The thicker pipe and rod inserts both furnish additional fuel and heat, and the rods decrease the area of the effective opening in the lance pipe; the oxygen stream thus gains greater velocity, and its eroding effect is increased.

The opening of tapholes in blast furnaces with the oxygen lance was the first successful application of cast-iron cutting. In this operation the end of the lance is heated with an oxyacetylene welding torch and is then placed against the cast iron in the taphole which is red-hot from the internal heat of the surface. Oxygen is then allowed to flow through the pipe and impinge against the heated spot in the tap hole. Owing to the combined action of the burning iron pipe and the oxygen stream, the cast iron is quickly pierced, and the molten metal can flow out.

With various modifications, oxygen lances are widely used for flame-cutting large sections of cast iron, steel, and other materials. For example, the lance is used for burning holes in salamanders; in these, after cooling, dynamite is placed, which is then exploded for final demolition.

Type 2 cutting ostensibly is an oxyacetylene cutting resort that extends the dimensional or depth range of standard cutting blowpipe operations and, therefore, is used primarily for severing thick or heavy masses of metal. It is seldom used alone, but as an aid to type 1 cutting. However, if the work is set up to permit the easy application of the regular lance cutting technique, it can progress independently. Per pound of metal removed, type 2 usually consumes more oxygen than the other types of cutting. This, however, is offset by the greatly increased value of the cutting service compared with other methods that may be used. Obviously, the surface produced by type 2 cutting is not so smooth as is produced by the other types, particularly type 1.

Wherever possible, oxygen-lance cuts should be made in a manner that will allow the slag and molten metal to flow out of the cut freely by gravity.

Type 3 *Flame Cutting.*—This technique was developed for the severing of the cast irons. It uses considerably more preheat than type 1 to start the cut and also to maintain it; in addition, it resorts to a definite flame oscillation during the cutting operation, a necessity with the cast irons, particularly those possessing carbon in the uncombined or graphitic state.

The resulting cut may be termed a "worked cut," for the metal originally in the kerf has, in reality, been "worked out" by the oscillating technique, which, if regularly maintained, causes a constant stream of slag and molten metal to flow through the kerf, preheating the base metal in the kerf as it passes through, which is thus prepared for further oxidation and displacement as the molten products are removed. The sidewise motion, or oscillation, of the flame is in the form of half circles or new moons at regular, short intervals (see Fig. 294). Thus, a cut is produced which is somewhat rougher than that produced by type 1 cutting and in which a greater proportion of the metal than with type 1 is removed by the mechanical or force properties of the high-velocity cutting oxygen. Owing to the wider kerf produced, more metal must be consumed and oxygen and acetylene consumption is greater than in type 1 flame cutting.

The preheating flames in type 3 cutting are caused to be highly carburizing; that is, they are made to carry a considerable excess of acetylene, and there results a long whitish feather in the flames beyond the small white inner cone (see Fig. 297). The length of excess acetylene streamer should be approximately equal to the thickness of the cast iron. This flame adjustment provides fuel for preheating beyond the tip of the blowpipe and consequently aids in maintaining preheat along the path of the cut as the acetylene combines with oxygen from the cutting oxygen stream.

The most essential thing in performing type 3 cutting is the maintenance of a steady and good degree of preheat at the starting point or top of the cut and a steady and uniform slag flow. In the case of the clean homogeneous cast irons, this is not difficult; and, in consequence, it is possible to make a relatively smooth-appearing cut.

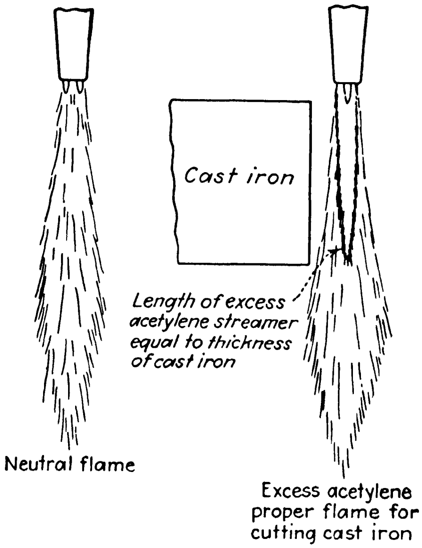

Cast iron
Length of excess acetylene streamer equal to thickness of cast iron
Neutral flame
Excess acetylene proper flame for cutting cast iron

FIG. 297.—Size of flame for type 3 cutting.

Cast-iron flame cutting appears to be limited at present to demolishing castings and to making alterations and repairs to machinery. Where heavy parts are to be removed, particularly in close quarters, the cutting torch saves time and money. Alterations to machines often require only a part of a casting to be cut away. Repairs of cracks or breaks in large cast-iron members by welding require preparation of the section by veeing. Here the oxyacetylene cutting torch is of great value.

Type 4 Flame Cutting.—Its principal use at the present time is for severing the so-called stainless steels, which resist oxyacetylene cutting by the simpler techniques of types 2 and 3. In addition to the usual preheating at the point where the cut is started, preheat is also applied along the entire face of the cut until it is brought to a bright-red color, where-upon the cutting operation is started and progressed through the part by the forward and backward reciprocating technique illustrated in Fig. 294.

As in type 3 cutting, the maintenance of a steady stream of liquid slag and molten metal is essential for a successful cut. Slag erosion probably is as important an agent in making cuts in the stainless steels as any other single function of cutting and determines the degree of uniformity attainable in cutting in these materials. By and large, type 4 cutting is rough cutting and calls for subsequent tool machining or grinding if a smooth finish is desired.

Type 5 *Flame Cutting.*—This technique is developed around the use of metals of relatively high cuttability to aid the cutting of metals of relatively low cuttability, as fluxes are used in certain welding operations to increase the fusibility of refractory oxides. There are a number of different techniques under this type of cutting, but in the main they have resort to cover or to cover and intermediate plates of low-carbon steel placed as jackets or interlaminations between the resistant materials to initiate good cutting conditions and, if laminated, to relay these conditions through the stack. The bottom and top jacket plates are sometimes used merely to produce sharp-cut edges in parts otherwise readily cuttable, in which case the operation is referred to as "stack flame cutting," previously described. Metals containing high nickel chrome can often be cut by type 5 cutting, and the cuttability of all of the less resistant materials is greatly improved by its technique.

One form of type 5 cutting uses a low-carbon steel rod or bar at the point of cutting to supply additional heat and slag to a cut in a resistant material, the work of the cutting blowpipe being thus supplemented. The bar or rod can be moved at the will of the operator to be available at or adjacent to the critical point of cutting. Castings or resistant materials are often cut quite readily by this means.

Anyone of the previous four techniques, types 1, 2, 3, and 4, may be employed in type 5 cutting, depending upon the specific nature of the resistance.

Cuttability of Ferrous Metals.—Certain alloy steels contain chromium, nickel, and other elements in sufficient amounts to make their cuttability much more difficult than carbon steels. Types of flame-cutting techniques, as described in previous sections, that can be used with various ferrous metals are given in Table XXII.

Manual Flame Cutting. *Freehand Flame Cutting.*—In freehand flame cutting, the hand cutting torch is both held and guided by the operator. The first oxyacetylene cuts were made by this method, and it is still widely employed in industry. The torch is held steadily but not tightly with the left hand supporting it a few inches back of the head and with the right hand on the handle in position to control the cutting oxygen trigger or lever. As in all manual crafts, the results obtained depend largely upon the skill of the operator. However, the operation is

TABLE XXII.—CUTTABILITY OF FERROUS METALS CLASSIFIED ACCORDING TO CUTTING METHODS

	Groups and/or subdivisions of cuttable metals	Approximate chemical range, per cent				Remarks
NOTE: This is the simple progressive type of oxyacetylene cutting used generally for the plain carbon steels.						
Type 1 cutting*		Carbon				
	Pure iron:					Preheat before cutting when carbon exceeds 0.30
	Electrolytic iron	0.01				
	Swedish iron	0.02				
	Low-carbon iron, rolled or wrought:					
	Charcoal iron	Up to 0.04				
	Wrought iron	0.04 max.				
	Low-carbon steel, rolled, wrought, or cast:					
	Rivet steel	0.10–0.15				
	Flange steel	0.15–0.30				
	Firebox steel	0.15–0.30				
	Structural steel	0.15–0.35				
	Steel forgings	0.20–0.45				
	Cast steel	0.20–0.45				
	Spring steel	0.90–1.10				
	High-carbon steel	0.80–1.60				
		Carbon	Copper	Nickel		
	Copper-bearing steel:					
	Plain	....	0.20–0.35			
	Seamless	0.10–0.20	1.00 max.	1.00		
		Carbon	Manganese	Silicon		
	Manganese steel:					
	Hadfield's	1.00–1.50	10.0–14.0			
	Silico	0.45–0.70	0.60–0.90	0.80–2.20		
	Silico	0.55–0.65	0.60–0.90	0.80–2.20		
		Carbon	Molybdenum	Chromium	Manganese	
	Molybdenum steel	0.15–0.60	0.20–0.35			
	Chrome-molybdenum steel	0.15–0.60	0.20–0.35	0.80–1.10	0.40–0.90	
		Carbon	Chromium	Manganese	Silicon	
	Low-chrome steel (Cromansil)	0.10–0.65	0.40–0.60	0.90–1.40	0.70–0.90	
	1 per cent chrome steel	0.90 max.	0.80–1.10			
		Carbon	Chromium	Vanadium	Nickel	
	Vanadium steel	0.90 max.	....	0.15 min.		
	Chrome vanadium steel	0.90 max.	0.80–1.10	0.15 min.		
	Nickel chrome steel	0.60 max.	0.50–1.50	....	1.25–3.75	
	4-6 chrome steel	0.25 max.				
	Nickel steel	....	....	....	5.00 max.	
			Phosphorus	Sulphur		
	Phosphorus steel	....	0.10			
	Sulphur steel (high-sulphur steel)	....	....	Up to 0.30		
		Carbon	Manganese	Silicon		
	Silicon steel:					Precautions necessary to prevent or modify air hardening in upper ranges of carbon and manganese.
	Structural sil. steel	0.30–0.40	0.50–0.80	0.15–0.50		
	Transformer steel	0.10 max.	....	Up to 4.00		
		Carbon	Tungsten	Silicon	Chromium	
	Tungsten steel	0.60–0.85	1.50–3.00	0.10–0.50	0.0–2.00	
			Aluminum	Chromium	Molybdenum	
	Aluminum steel	....	1.00	1.00	0.50	

* See text pages for description of the various cutting techniques classified as types 1, 2, 3, 4, and 5.

TABLE XXII.—CUTTABILITY OF FERROUS METALS CLASSIFIED ACCORDING TO CUTTING METHODS.—(*Continued*)

	Groups and/or subdivisions of cuttable metals	Approximate chemical range, per cent				Remarks
Type 2*	NOTE: This type is known commercially as oxygen-lance cutting. Its scope parallels type 1 cutting and, in addition, is used at times as an aid to types 3 and 4 cutting. See text for more detailed description.					
Type 3 cutting*	NOTE: This type is generally referred to as cast-iron cutting because it was developed for cutting the cast irons.					
		Carbon	Silicon			
	Cast iron:					
	White cast iron	2.50 and up	1.50 max.			
	Grey cast iron	2.75–3 75	1 50-3.00			
	Malleable cast iron	2.50	1.00			
	Semisteel	2.00–3.00	1 50-3.00			
	Duriron	0.75	15.00			
		Carbon	Tungsten	Chromium	Vanadium	
	High-speed steel	0.60–0.90	10.0–20 0	5 00	2.00	Beyond 20 per cent tungsten cutting is impractical.
		Carbon	Chromium	Nickel		
	High-nickel steel	0.50 max.	30 00–50.00			
Type 4 cutting*	NOTE: This type of oxyacetylene cutting is at the present time most commonly used for cutting the so-called stainless (or rust-resisting) steels.					
		Carbon	Chromium	Nickel		
	Stainless steels:					
	Low-carbon chromium steels	0.12	12.00–15.00			
		0.12	15 00–18 00			
	High-carbon chromium steels	0 30	12.00-14 00			
		0 60	16 00-18 00			
	Chrome nickel steels	0 05-0.20	16.00–20.00	7 00-10 00		
Type 5*	NOTE: This is a composite type of oxyacetylene cutting that utilizes the characteristics of readily cuttable steels to aid the cutting of steels of lowercut tability. See text for more detailed description.					

* See text pages for description of the various cutting techniques classified as types 1, 2, 3, 4, and 5.
SOURCE: International Acetylene Association.

really a simple one, and the average conscientious workman soon acquires proficiency. In addition to following the line of cut steadily and without wavering, the operator should look down into the cut and watch the drag, taking care that the flow of slag or oxide is clean and unimpeded through the metal. The torch should be moved forward just fast enough to allow combustion to take place throughout the material, as the cut progresses.

More than 20 different variables, aside from the very important one termed the "human" element, affect freehand flame-cutting performance. Clearly, therefore, it is hardly possible to compile cutting tables allowing for all these factors. However, the accompanying table may be taken as representative of fair average practice in type 1 freehand flame cutting of mild steel, not preheated. Oxygen and acetylene consumptions for cutting the various thicknesses of mild steel are given in cubic feet per hour and also per linear foot of cut.

TABLE XXIII.—HAND FLAME CUTTING TABLE FOR ⅛- TO 12-IN. THICKNESSES FOR CLEAN MILD STEEL—NOT PREHEATED—TYPE 1 CUTTING ONLY

Thickness of steel, in.	Diameter of cutting orifice, in.	Oxygen pressure, lb. per sq. in.	Cutting speed, in. per min.†	Gas consumptions†			
				Cu. ft. per hr.		Cu. ft. per lin. ft.‡	
				Oxygen	Acetylene	Oxygen	Acetylene
⅛	0.0380–0.0400	15–23	20 –30	45– 55	7 – 9	0.37– 0.45	0.06–0.07
¼	0.0380–0.0595	11–20	16 –26	50– 93	9 –11	0.63– 0.72	0.08–0.11
⅜	0.0380–0.0595	17–25	15 –24	60–115	10 –12	0.80– 0.96	0.10–0.13
½	0.0465–0.0595	20–30	12 –22	66–125	10 –13	1.10– 1.14	0.12–0.17
¾	0.0465–0.0595	24–35	12 –20	117–143	12 –15	1.43– 1.95	0.15–0.20
1	0.0465–0.0595	28–40	9 –18	130–160	13 –16	1.78– 2.89	0.18–0.29
1½	0.0595–0.0810	40	6				
2	0.0670–0.0810	22–50	6 –13	185–231	16 –20	3.55– 6.16	0.31–0.53
3	0.0670–0.0810	33–55	4 –10	240–290	19 –23	5.80– 12.00	0.46–0.95
4	0.0810–0.0860	42–60	4 – 8	293–388	21 –26	9.70– 14.64	0.65–1.05
5	0.0810–0.0860	53–70	3.5– 6.4	347–437	24 –29	13.66– 19.83	0.91–1.37
6	0.0980–0.0995	45–80	3.0– 5.4	400–567	27 –32	21.00– 26.70	1.19–1.80
8	0.0995	60–77	2.6– 4.2	505–615	31.5–38.5	29.30– 38.84	1.83–2.42
10	0.0995	75–96	1.9– 3.2	610–750	36.9–45.1	46.90– 64.20	2.57–3.84
12§	0.1200	69–86	1.4– 2.6	720–880	42.3–51.7	67.70–103.00	3.98–6.05

† As the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data, therefore, have been omitted from this table. For acetylene pressure data, see cutting apparatus manufacturers' charts.

‡ Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, dirty or poor material. Highest speeds and lowest gas consumptions per linear foot are for experienced operators, long cuts, clean and good material.

§ Beyond 12-in. thickness, the critical data of manual cutting practices are greatly affected by the condition of the metal and the skill of the operator, resulting in wide ranges of data. In view of this, the table has been terminated at the 12-in. thickness.

The reader is referred to table No. XXIV giving data on Machine Cutting wherein the thickness range has been extended to 20 in.

SOURCE: International Acetylene Association.

Freehand "Guided" Flame Cutting.—Under freehand "guided" flame cutting are classified such operations as circle cutting and drawing the torch head along a bar or straight edge which acts as a guide. Circles or disks can be cut accurately with a straight-head hand torch, using a circle-cutting attachment. This consists of a short rod with a clamp at one end that fits over the torch head and an adjustable center point that can be set at any radius within the capacity of the device. The center point is placed in a punch mark and the torch turned around it, thus cutting a circular shape. Resting the torch head against a straightedge or other guide is helpful in certain cases in making smooth hand cuts. A variation of this is an attachment with small wheels which rest and roll on the surface of the work.

Rivet Flame Cutting.—Heretofore, rivets have been removed by actual cutting off of the head flush with the plate, a bent tip being used, or by piercing. These methods, still preferred for certain work, come under the head of flame cutting. However, by a later improvement method, the rivet heads are now consumed by surface oxidation, and this operation is included under flame machining.

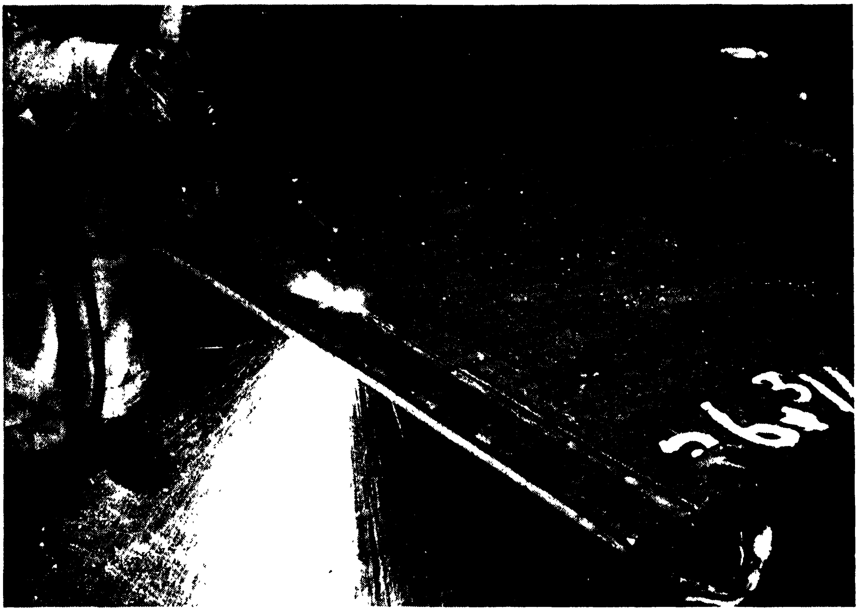


FIG. 298.—Freehand "guided" flame cutting. (*Courtesy of The Linde Air Products Company.*)

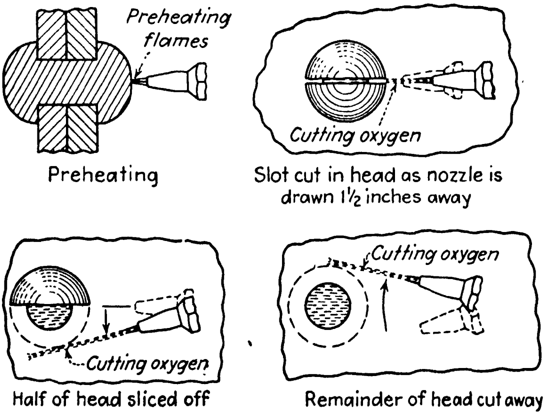


FIG. 299.—Manipulation of standard cutting nozzle in removing head of rivet. (*Courtesy of The Linde Air Products Company.*)

Machine Flame Cutting.—For many operations, the advantage of mechanically holding, guiding, and advancing the torch over the work was recognized at an early period in the history of flame cutting. It was evident that the substitution of mechanical for manual torch operation, wherever practicable, would effect better workmanship and greater accuracy and economy. The introduction and development of oxyacetylene cutting machines to fill this demand followed naturally.

Oxyacetylene Cutting Machines.—From crude beginnings, oxyacetylene cutting machines have been improved to the point where they are now comparable with machine tools. These machines are capable of making flame cuts with a flexibility equivalent to that attainable in woodworking with a jig saw and of such high quality and accuracy that for usual purposes little or no finishing is required. Oxyacetylene cutting machines now available are manual or motor-driven, partly or almost fully automatic, portable or stationary, and have various capacities suitable for practically all classes of work of almost any size or thickness.

Some machines are equipped with two or more cutting torches, centrally controlled and guided, and will flame-cut a like number of identical shapes simultaneously, thereby effecting marked economies where high production rates are essential. Still other types of machines crawl around pipes, making one or two square or beveled cuts as desired. Nearly every conceivable requirement is covered by the wide assortment of machines now manufactured.

Straight-line Machine Flame Cutting.—As might be expected, straight-line machine flame cutting is even simpler than freehand flame cutting. Once the machine and gas pressures have been set, the torch follows the line of cut automatically and need only be advanced uniformly, at proper speed. The latter function is performed either by turning a crank or handwheel or by an electric motor. Some portable motor-driven machines run on sections of straight track, which guide the machine and the torch mounted upon it. During the progress of the cut, the operator should watch the drag and the flow of slag or oxide to prevent pocketing or loss of cut. The speed and gas pressures should be adjusted to the ranges given in Table XXIV.

Machines should be set up to eliminate jar and vibration during cutting, and the work on metal being cut should be supported to ensure continuity of cut without interference, as well as to prevent the parts or scrap pieces from falling when cut and endangering the machine or the operator. In heavy flame cutting, particular attention should be given to proper apparatus setup, including manifolds, regulators, and hose of suitable type and sufficient capacity to ensure sufficient oxygen and acetylene at the required pressures and continuous operation of the cut.

Shape Machine Flame Cutting.—Shape cutting is the outstanding example of the extreme flexibility of the process. Regular or irregular shapes of almost any size or thickness, no matter how complex, may be machine-flame-cut with ease. Machines for this work are mostly motor-driven. Some are fitted with tracing devices which are manually guided around the outline of a drawing or template of the required shape. One or more torches are mounted on the machine so as to describe exactly the same motion as the tracing device over the work, thereby flame cutting the shape traced.

TABLE XXIV.—MACHINE FLAME CUTTING TABLE FOR ⅛- TO 20-IN. THICKNESSES FOR MILD STEEL—NOT PREHEATED—TYPE 1 CUTTING ONLY*

Thickness of steel, in.	Diameter of cutting orifice, in.	Oxygen pressure, lb. per sq. in.	Cutting speed, in. per min.‡	Gas consumptions†			
				Cu. ft. per hr.		Cu. ft. per lin. ft.‡	
				Oxygen	Acetylene	Oxygen	Acetylene
⅛	0.0250–0.0400	15– 23	22 –32	40– 55	7– 9	0.34– 0.36	0.05– 0.06
¼	0.0310–0.0595	11– 35	20 –28	45– 93	8–11	0.45 - 0.66	0 08– 0.08
⅜	0.0310–0.0595	17– 40	19 –26	82– 115	9–12	0.86– 0.89	0 09– 0.09
½	0.0310–0.0595	20– 55	17 –24	105– 125	10–13	1.04– 1.24	0.11– 0.12
¾	0.0380–0.0595	24– 50	15 –22	117– 159	12–15	1.45– 1.56	0.14– 0.16
1	0.0465–0.0595	28– 55	14 –19	130– 174	13–16	1.83– 1.86	0.17– 0.19
1½	0.0670–0.0810	55	12 –15	240	14–18	3.20	0.23– 0.24
2	0.0670–0.0810	22– 60	10 –14	185– 260	16–20	3.70– 3.72	0.29– 0.32
3	0.0810–0.0860	33– 50	8 –11	240– 332	18–23	6.00– 6.04	0 42– 0.45
4	0.0810–0.0860	42– 60	6.5– 9	293– 384	21–26	8.53– 9.02	0.58– 0.65
5	0.0810–0.0860	53– 65	5.5– 7.5	347– 411	23–29	10.97– 12.62	0.77– 0.84
6	0.0980–0.0995	45– 65	4.5– 6.5	400– 490	26–32	15.10– 17.78	0 98– 1.16
8	0.0980–0 0995	60– 90	3 7– 4.9	505– 625	31–39	25.52– 27.30	1.59 1.68
10	0.0995–0.1100	75– 90	2 9– 4 0	610– 750	37–45	37.50 - 42.10	2 25– 2.55
12	0.0110–0.1200	69–105	2.4– 3.5	720– 880	42–52	49.70– 60.00	2.97– 3.50
14	0.0110–0.1200	105	2.0– 3.2	830–1,045	48–59	65.20– 83.00	3.69– 4.80
16	0.1285–0.1600	110	1.8– 3.0	935–1,360	57–70	90 60–104.00	4.67– 6.33
18	0.1495–0.1600	120	1.7– 3.0	1,045–1,680	65 83	112 10–123.00	5.53 7.65
20	0.1610–0.2000	135	1.5– 3.0	1,155–2,050	75 99	136.70–154.00	6.60–10.00

* The apparent inconsistencies that will be noted in some of the columns are due to the fact that there does not exist a straight-line relationship among the elements of pressure, speed, and orifice sizes for the range of apparatus data from which this table was devised.

† As the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data have been omitted from this table. For acetylene pressure data, see cutting-apparatus manufacturers' charts.

‡ Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, and dirty or poor material. Highest speeds and lowest gas consumptions per linear foot are for experienced operators, long cuts, and clean and good material.

SOURCE: International Acetylene Association.

Some machines are fitted with motor-driven guide rollers, which automatically follow a template of the required shape, simultaneously controlling the movement of the torch so as to flame-cut the same shape. Magnetized rollers, which adhere to the steel templates as they advance automatically around the contour, are a feature of certain machines.

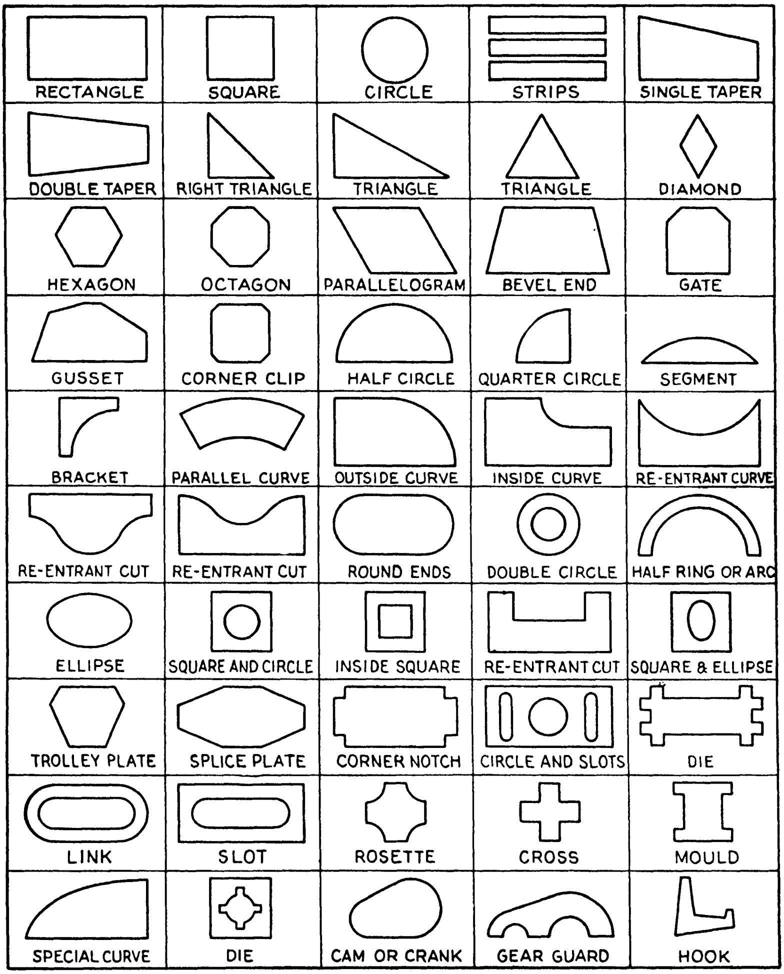


FIG. 300.—Examples of shape cutting.

Some typical shapes, for which machine flame cutting is adapted, are illustrated in Figs. 291 and 300.

Circular Machine Flame Cutting.—The circle is, of course, one of the simplest and most regular of the geometrical shapes. However, it is so frequently encountered in machine-flame cutting of disks, flanges, heads, and similar parts, that it will be discussed separately.

Nearly all oxyacetylene cutting machines can be adapted to circular cutting. With some, a radius rod with an adjustable center point is furnished. The point is placed in the center punch mark of the circle, and the machine and cutting torch travel around the circumference at the radius set. Machines fitted with guide rollers to follow templates require only a circular template of the proper size.

In circular cutting, particularly of holes, it is customary to make a short "lead-in" cut just through the scrap, so as to have the finished cut smooth and unmarred at the starting point.

Precision Machine Flame Cutting.—One machine-flame-cutting technique that produces especially high quality and accurate cuts is sometimes distinguished by the name "precision machine-flame cutting."

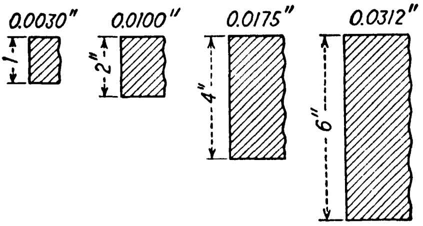


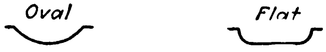
FIG. 301.—Cross-cut tolerances, precision machine cutting practices.

The detail cutting technique is confined strictly to type 1 cutting. Both preheating flames and the cutting oxygen must be carefully adjusted for the thickness of the part to be cut. Although with different experiences in precision flame cutting the practices may vary from exact agreement, there is nevertheless a rather close agreement when referred to a standard drag for all methods or types of apparatus.

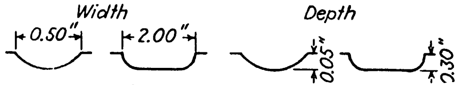
The degree of precision attained in modern precision-machine-flame-cutting practices has been within several thousandths of an inch in material up to 2 in. in thickness; that is, the cut surfaces were true as to cross-sectional squareness to within this amount. Longitudinally, the degree of precision depends upon the trueness of the guide rails of the cutting machine, the clearance of operating mechanism, and the regularity of the propelling unit, just as with machine tools. The more recent straight-line and shape cutting machines are constructed so as to maintain very close traverse alignment; however, much depends upon the sensitivity of the tracing mechanism, which, if not carefully adjusted as to grip and speed, will defeat the precision of the cutting machines beyond this point. Figure 301 typifies the approximate average cross-sectional cutting tolerance range for type 1 cutting for thicknesses up to and including 6 in.

Special Machine Flame Cutting.—In addition to the types of machine flame cutting already discussed, there exists besides quite a field of special applications for the process. This field includes cutting of pieces that are not flat, cutting in different planes or at different levels and angles on the same piece, cutting sections of variable thickness, and similar work. For example, digester shell plates are dished and formed like orange peelings, although of uniform thickness. They may be machine-flame-cut or trimmed to size, with beveled edges for calking where desired, very satisfactorily and economically. Severing of I beams and other structural shapes or rails requires positioning of the torch to cut at different heights and angles. Cutting off round bar stock is typical of straight-line cutting through variable thickness.

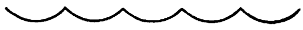
Many of these special problems have been solved satisfactorily with existing oxyacetylene cutting machines or adaptations of these machines.



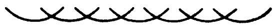
(a) Types of contours



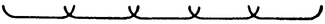
(b) Typical dimensional range



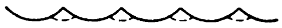
(c) Simple planing



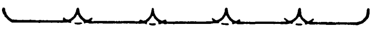
(d) Over-lap Oval cuts



(e) Over-lap Flat cuts



(f) Trailing oval cuts



(g) Trailing flat and oval cuts.

Fig. 302.—Types of planing and turning cuts used in flame machining.

Others have required special machines. Much is being done along these lines in the way of devising and perfecting machines to cover adequately the special fields of cutting.

Flame Machining.—In flame machining, each operation is more or less a problem in itself, calling for a coordination of nozzle tooling and metallurgical control.

Compared with standard tool machining, the operations of flame machining developed to date classify as rough machining; however, surface tolerances to within $\frac{1}{16}$ in., as measured by depth gauges, are being maintained in some operations. Although to date most of the work done in this new field of cutting has been in the plain carbon steels, there is good reason to expect that the operations herein described will apply equally well to certain alloy steels.

Flame Planing.—There are several types of tangential cuts that are classed under flame planing. The principal differences among them relate primarily to the character of application and the tolerance or degrees of surface regularity attained or permitted. Per flame, they all produce a relatively milling type of cut. The profile of the cut can, however, be varied considerably, as also can the general surface of a part. Flame planing can be either manual or mechanical. The subclassifications are:

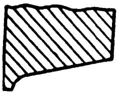
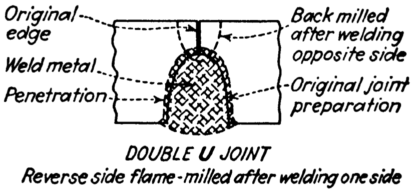


Fig. 303.—Profile of milling cut made by flame machining.

1. Deseaming. This process of flame planing is being used extensively for removing cracks or seams in billets, slabs, and rounds en route to the various finishing departments of steel mills and in the steel foundry for exploring and cleaning out cracks and sand holes (see Fig. 302*a* and *b*).

2. Hogging. This application of flame planning performs the services of removing superfluous metal in steel castings, either purposely arranged or caused by defective conditions at the time of pouring, and of removing risers and sprues whose location or character is such as to make it difficult or impossible to remove by ordinary or type 1 flame cutting.

3. Surface planing. This operation is a step beyond that of deseaming, in that the cuts are caused to be adjacent to one another, and the removal of wide surfaces is thus possible. When surface planing is accomplished mechanically, the dimension tolerances as to depth and width of cut can be kept to within $\frac{1}{16}$ to $\frac{1}{8}$ in. of the finished surface. Surface regularity in flame planing is a matter of the selection of style of profile and the arrangement of the cutting flames with respect to their center-lines. Figure 302*c*, *d*, *e*, *f*, and *g* shows some of the combinations and the resulting surfaces.


Original edge
Weld metal
Penetration
Back milled after welding opposite side
Original joint preparation
DOUBLE U JOINT
Reverse side flame-milled after welding one side
Fig. 304.—Double-U joint. A back-milling flame-machining operation.

Milling.—Under this classification are grouped those cuts which simulate the style of cuts produced by rotary mills in tool machining. The most popular applications of flame milling at present consist in milling the edges of plates in the general forms shown in Fig. 303 and backmilling partly welded U-type butt joints as shown in Fig. 304.

The cutting of concave types of fillet along the edges of rolled steel plates or bars is a development of flame milling that promises a quick and economical substitute for machined fillets. The principal values of such cuts lie in the improvement of the appearance or salability of objects built of square edged plates and in removing sharp edges about working parts of machines. Figure 305 illustrates the range of fillet profiles that are considered possible by flame-milling cuts. Several of these profiles are readily produced with the ordinary deseaming nozzle.

Turning.—The turning cuts are shown in Fig. 306. The cut at *A* is a typical deseaming application of the flame operating under a screw feed. The resulting threads could be made deeper by merely repeating the operations with the same nozzle, oxygen pressure, and flame angle at the lower depth. The cut at *B* shows the result of multipasses of the flame on zero feed, producing a deep straight-sided cut. A modification of the procedure at *B* is utilized where a spindle or journal cut is desired. This is shown at *C*. The cut is started by successive centric passes of the flame as at *B*, then is progressed by directing the cutting flame against the vertical wall of the original milling cut. The result is a lighter feed but a greater depth of cut which is more economical where large amounts of metal are to be removed. Cuts of these general types can be varied considerably as to width and depth by changing the relation among the flame angle, oxygen pressure, and velocity of the work.

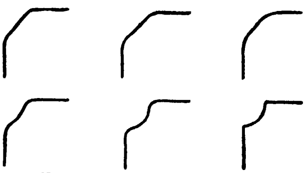


Fig. 305.—Some of the fillet profiles obtained by flame machining.

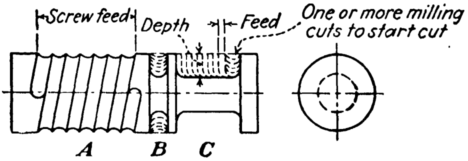


Fig. 306.—Types of milling cuts which can be made by multipasses of the planing nozzle.

These adjustments must, however, be kept within the range of cuttability; that is, there is a point where these functions can, separately or collectively, be either insufficient or excessive for usable or practical flame turning.

Drilling and Boring.—Figure 307 shows a form of flame drilling consisting in depressing a round hole in the end of a billet for centering or piercing purposes. The dimensions of the resulting hole can be made uniform and its walls straight-sided provided that the nozzle is properly held during the drilling operation. The oxygen lance is also a valuable tool for drilling operations, particularly of considerable depth, beyond the reach of cutting tips.

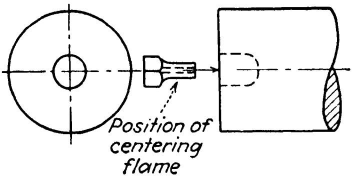


Fig. 307.—Centering for flame drilling.

Rough boring through the means of a compound setting of the cutting flame classifies with flame drilling and enlarges the range of work of this general character. Its application is more a problem of tooling, in that the slag and molten metal from the cuts are prevented from interfering with the cutting and the operation of the cutting nozzle.

OXY-OTHER-FUEL-GASES CUTTING

Besides acetylene, a number of other higher flame temperature fuel gases have been employed for cutting ferrous metals, with varying degrees of success. The more important of these are: hydrogen, city gas, natural gases, coke-oven gas, ethylene, and the higher petroleum distillates, including methane, ethane, propane, and butane. Their combustion constants are given in Table XXV.

TABLE XXV.—COMBUSTION CONSTANTS OF FUEL GASES

Gas	Chemical equation for complete combustion	Heat value, B.t.u. per cu. ft.	Flame temperature with oxygen, °F.
Acetylene	$C_2H_2 + 2\frac{1}{2}O_2 = 2CO_2 + H_2O$	1,433 net	6300
Hydrogen	$H_2 + \frac{1}{2}O_2 = H_2O$	275.1 net	5400
City gas	Typical mixture	300–800 net	4600
Natural gas	Typical mixture	800–1,200 net	4600
Coke-oven gas	Typical mixture	500–550 net	4600
Methane	$CH_4 + 2O_2 = CO_2 + 2H_2O$	913.8 net	5000
Ethane	$C_2H_6 + 3\frac{1}{2}O_2 = 2CO_2 + 3H_2O$	1,631 net	5100
Propane	$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$	2,309 net	5300
Butane	$C_4H_{10} + 6\frac{1}{2}O_2 = 4CO_2 + 5H_2O$	2,999 net	5300
Ethylene	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$	1,530 net	5100

All of these gases, except hydrogen, are hydrocarbons, and thus give off carbon dioxide (CO_2) and water vapor (H_2O) as products of complete combustion.

The optimum gas ratios and equivalent volumes of oxygen to acetylene, city gas, natural gas, and propane required for gas cutting the same work at the same speed are shown in Table XXVI.

TABLE XXVI.—EQUIVALENT FUEL-GAS AND PREHEATING-OXYGEN VOLUMES FOR CUTTING

Fuel gas	Optimum ratio, oxygen to fuel gas	Gas consumption, cu. ft. per hr.	
		Preheating oxygen	Fuel gas
Acetylene	1.7 to 1	17	10
City gas	0.75 to 1	56	75
Natural gas	2.0 to 1	56	28
Propane	4.5 to 1	54	12

The values in Table XXVI are correct only when each fuel gas is utilized at its maximum efficiency. In practice, the operator has difficulty in adjusting the gas ratio of gases other than acetylene to even approximately correct values, because of the lack of a definite starting point, such as the neutral flame in the case of acetylene. As a rule, even experienced operators tend to adjust the gas ratio to much higher values than those which are considered best. This, of course, brings about the use of much more oxygen than otherwise would be required.

What is more, when certain fuel gases are used, the oxygen requirements for the cutting jet are also greater than when acetylene is used. This is especially true when the preheating-gas consumptions are large and the resulting gases of combustion are sufficient to pollute the cutting oxygen jet. In such instances, a noticeable reduction in the cutting efficiency may result.

ARC CUTTING

The arc-cutting process is essentially the melting of metal along a desired line by the application of the electric arc.

Because of its very high temperature and its low cost of heat production, the electric arc is especially suitable for the cutting of those metals which cannot be very readily oxidized, such as cast iron, manganese steel, and nonferrous metals.

The smoothness and the accuracy of the cut obtained with the electric arc are not so good as those obtained with the flame-cutting process; but in cases where smoothness and accuracy are not desired, as in the cutting of scrap materials, arc cutting is much cheaper than flame cutting.

Arc cutting may be used for the beveling or shaping of parts prior to the actual welding, as well as for the removing of incorrectly applied deposits and for the smoothing off of excess reinforcement.

Since there is no great action tending to force the molten metal out of the cut, some provision must be made to permit the molten metal to drop or run out of the cut, regardless of the position the work is in. This may be done by starting the cut at some point from which the molten metal may readily flow owing to the force of gravity.

The speed of cutting with the electric arc is usually fairly high.

Carbon-arc Cutting.—In carbon-arc cutting, an arc is drawn between a carbon or graphite electrode and the sections to be cut.

Carbon electrodes are most frequently used, but they do not stand up very long under the high heat required in arc cutting. Graphite electrodes may be preferred at times because of the lower resistance that they set up to the flow of current, it being thus possible to use higher currents.

Direct current is generally used in carbon-arc cutting, with the setup of straight polarity. Alternating current may also be employed.

Special electrode holders may be required for carbon-arc cutting, especially if large electrodes are used. These special holders usually have a long shank as well as a shield to protect the operator's hand from the intense heat.

The carbon arc may be used for cutting both light and heavy plates where rough work is satisfactory.

In the cutting of plates up to ½ in. in thickness, the arc is simply advanced along the section to be cut. The rate of cutting is equal to the rate at which the metal is melted away. The cutting may be done in any position, but best results are obtained when the work is in a horizontal plane. The angularity of the electrode to the work depends on the position of the work. For vertical cutting, the electrode should be pointed downward. With the work in a horizontal position, the electrode may be held either vertical or slightly forward.

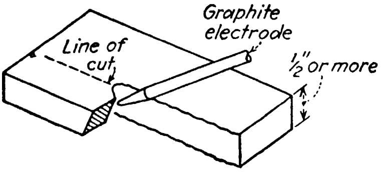


Fig. 308.—Carbon-arc cutting of heavy plates.

For plates over ½ in. in thickness, the cutting procedure should be such that the bottom of the cut is advanced slightly ahead of the top of the cut. The resultant undercut permits the molten metal to run off very easily. If the work is in a vertical position, the cut should be started at the bottom. With the work in a horizontal position, the electrode should be slanted backward, and the cut should be started at the bottom surface of the plate (see Fig. 308). Then, with the electrode pointing forward, the cut may be made into the plate.

The width of the cut depends on the thickness of the material, the size of the electrode, and the skill of the operator in cutting in a straight line; of course, the thicker the material, the wider the cut.

Table XXVII.—Current Values for Arc Cutting*

Graphite Electrode Diameter, In.	Current, Amp.
¼	Up to 200
⅜	200– 400
½	300– 600
⅝	400– 700
¾	600– 800
⅞	700–1,000
1	800–1,200

* Source: American Welding Society.

The size of the electrode and the amount of current used determine the speed of cutting, as well as the depth of the cut. Some recommended current values and graphite-electrode sizes are tabulated in Table XXVII.

Since arc cutting is a melting process rather than an oxidation process, cast iron and rolled steel may be cut at the same speed. Some arc-cutting speeds are shown in Table XXVIII.

TABLE XXVIII.—ARC-CUTTING SPEEDS WITH CARBON ELECTRODES*

Thickness of material, in.	Current, amp.	Cutting speed, in. per min.
¼	400	15
⅜	400	12
½	400	10
⅝	400	7
¾	400	4
1	600	3.2
1½	600	2.4
2	600	1.8
3	600	1.1
4	600	0.7
6	800	0.4
8	800	0.3
10	800	0.2
12	800	0.15
14	1,000	0.10
16	1,000	0.06

* SOURCE: American Welding Society.

The carbon arc is also successfully employed in the cutting of rivet heads. If the work is in the vertical position, best results will be obtained. If the work is in a horizontal position, the rivets may be successfully cut from the top or the bottom sides of the plates. In cutting from the bottom, the force of gravity will cause the molten metal to drop off; in cutting from the top, an air blast must be used to remove the molten metal.

Metallic-arc Cutting.—In metallic-arc cutting, an arc is struck between a coated electrode and the work to be cut.

Because of the high cost of the electrodes, cutting with coated electrodes is not very widely employed; but this process may be used to advantage for cutting in many cases, especially when the gas torch and the carbon electrode are not available.

Because of the insulating effect of the coating, it is possible to use coated electrodes in tight spots where neither the carbon arc nor the flame-cutting process would be practical.

Ordinarily, gas- and slag-producing electrodes may be used for arc cutting, with the latter being generally employed because they permit the use of higher currents. If desired, special electrodes may be used, especially those which, in the heat of the arc, give off oxygen. The oxygen helps in oxidizing the metal and in increasing the cutting speed.

Cutting of light-gauge metals may be done with the coated electrode, but this method is not employed very often. Plates, 3/8 in. in thickness or lighter, can be cut by simply moving the electrode along the line of cut. For heavier plates, it is necessary to work from the underside of the plate, so that the molten metal and slag may have a chance to drop or run off.

The cut may be started at the edge of the plate, or a hole may be burned through the plate, and thus the cut may be started at any desired point.

To keep the metal and the slag flowing out of the cut, a short arc should be held and the electrode should be kept pushing closely up in the slot, with the tip of the electrode being pushed right into the molten crater and manipulated with an up-and-down motion (see Fig. 309). The upward motion should be very fast, and the downward motion should supply a "pushing" effect, thus helping to force out the molten metal and slag.

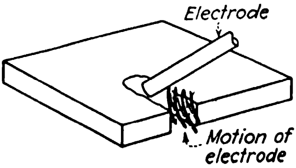


FIG. 309.—Cutting with coated electrode.

The width of the cut does not vary much for electrodes up to 1/4 in. in diameter.

Common sizes of coated electrodes for cutting purposes are 5/32, 3/16, or 1/4 in. Electrodes smaller than 5/32 in. in diameter are not recommended, for they heat up quickly and melt away under the high currents used.

The speed of arc cutting with coated electrodes depends on the diameter of the electrodes and on the current used. Approximate values are shown in Table XXIX.

TABLE XXIX.—ARC-CUTTING SPEEDS WITH METALLIC ELECTRODES

Plate thickness, in.	Cutting speed, in. per min.		
	5/32-in. electrode	3/16-in. electrode	1/4-in. electrode
1/4	12.0	15.0	21.0
1/2	7.0	9.0	11.0
3/4	4.25	5.5	6.7
1	2.5	3.7	4.6
1 1/4	1.6	2.4	3.2
1 1/2	1.0	1.7	2.3
1 3/4	0.6	1.3	1.8
2	0.4	1.0	1.4

Coated electrodes are often used to pierce holes in plates, where punching and shearing cannot be done (see Fig. 310).

High currents must be used for piercing purposes. After the arc is struck at the point where the hole is desired, the electrode should be moved in a circular motion equal to the diameter of the proposed hole until the metal is melted. The electrode is then pushed down against the molten metal, and the circular motion kept up at the same time. This operation, if continued, will cause the electrode to melt a hole through the plate.

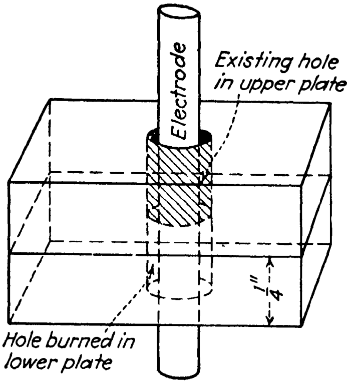
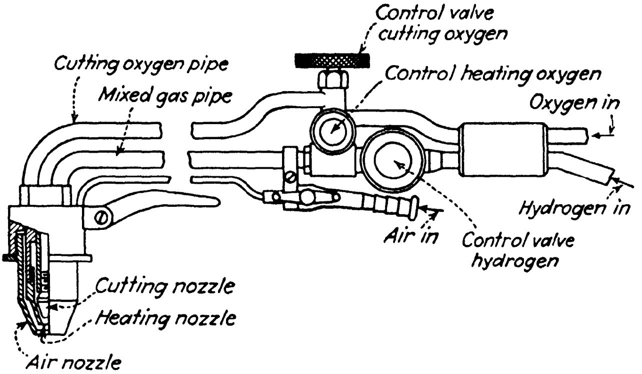


Fig. 310.—Burning hole in plate with coated electrode.

The coated-electrode cutting process can be used readily to cut alloy steels and many nonferrous metals. In this application, coated electrodes of an analysis somewhat similar to the work being cut should be used.



	Pressure, lb. per sq. in.			
Depth of water, ft.	Oxygen	Hydrogen	Air	Water
20	55	15	10	7
40	65	25	20	15
80	80	40	35	30
120	100	60	55	50

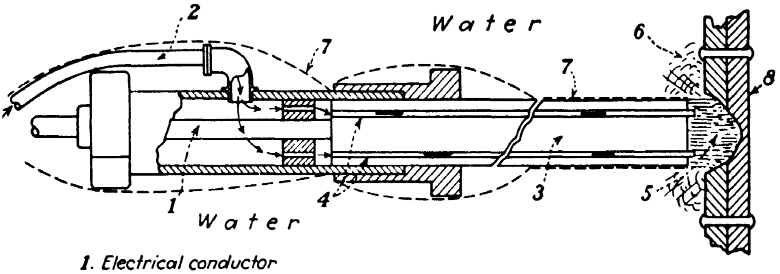
Fig. 311.—Torch designed on the principle of the compressed air jacket. (Grafton.) (*Courtesy of American Welding Society.*)

UNDERWATER CUTTING

The cutting of submerged metals may be done by means of oxyhydrogen, oxyacetylene, or oxyelectric torches.

The oxyhydrogen torch is fitted with a bell, or sheath around the tip. This bell is filled with compressed air to supply additional or atmospheric oxygen for combustion of the hydrogen and also to hold the water away from the preheating flames and the cutting area.

The oxyacetylene torch is used for underwater cutting at shallow depths, usually less than 35 ft. At greater depths, acetylene cannot be safely used because of the high fuel-gas pressure required to overcome the hydraulic head. Thus, hydrogen must be employed. When acetylene is used, considerably more compressed air must be supplied.



1. *Electrical conductor*
2. *Oxygen connection*
3. *Carbon electrode*
4. *Small pipes through electrode by which oxygen reaches the tip*
5. *Flaming arc*
6. *Vaporous cavity in which the arc burns the metal to be cut*
7. *Covering of friction tape to insulate the torch*
8. *Steel plates being cut*

Fig. 312.—Diagram of the principal parts of the oxyelectric underwater cutting torch used by Sherrett. (*Courtesy of American Welding Society.*)

As in the above two processes, oxyelectric cutting utilizes oxygen as the cutting medium. The oxyelectric torch consists of a perforated carbon or metallic electrode held in an insulated handle carrying a shield. The arc, when struck and maintained, preheats the metal and at the same time provides a sheath of gas around the oxygen which issues from the perforations in the electrode.

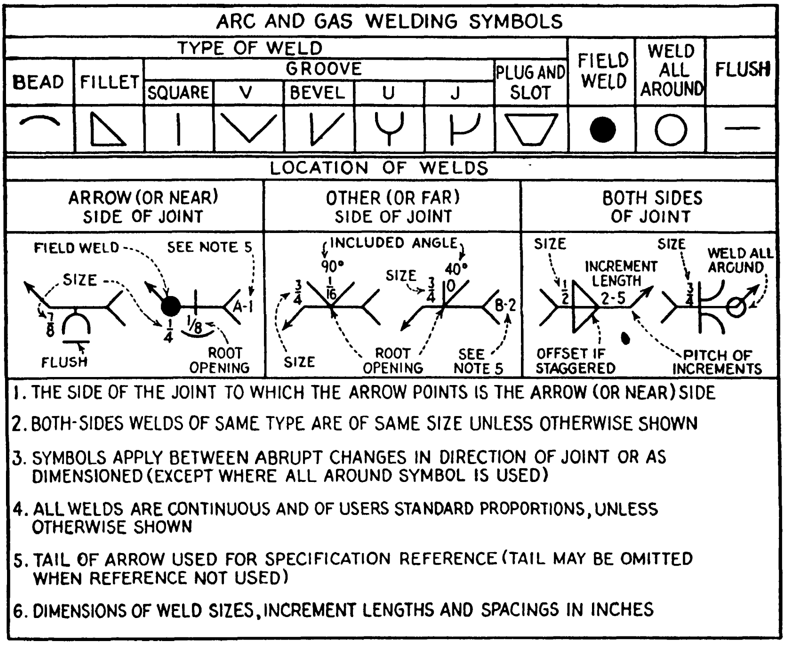
Underwater cutting has been done quite successfully, especially with hydrogen, at depths of 135 ft. or more on sunken ships of all types, bridge caissons, and steel piling.

CHAPTER XVI

WELDING SYMBOLS AND THEIR USE

Welding symbols have been developed and standardized by the American Welding Society. The instructions for their use, as given in this chapter, were issued by the society in October, 1940, and have been included here through its courtesy.

The symbols are a means of conveying complete information from the designer to the workman. The old practice of writing the word "weld" on a working drawing with an arrow pointing to the joint in question or a note, such as "To be welded throughout," on the bottom of the drawing, is satisfactory for unimportant work; but when structures the failure of which would endanger life and property are to be welded, simple and specific means must be used to convey the ideas of the designer to the shop.



1. THE SIDE OF THE JOINT TO WHICH THE ARROW POINTS IS THE ARROW (OR NEAR) SIDE
2. BOTH-SIDES WELDS OF SAME TYPE ARE OF SAME SIZE UNLESS OTHERWISE SHOWN
3. SYMBOLS APPLY BETWEEN ABRUPT CHANGES IN DIRECTION OF JOINT OR AS DIMENSIONED (EXCEPT WHERE ALL AROUND SYMBOL IS USED)
4. ALL WELDS ARE CONTINUOUS AND OF USERS STANDARD PROPORTIONS, UNLESS OTHERWISE SHOWN
5. TAIL OF ARROW USED FOR SPECIFICATION REFERENCE (TAIL MAY BE OMITTED WHEN REFERENCE NOT USED)
6. DIMENSIONS OF WELD SIZES, INCREMENT LENGTHS AND SPACINGS IN INCHES

FIG. 313.—Legend for use on drawings specifying arc and gas welding.

This scheme, with its legends, numerical data, and instructions, may appear voluminous, but it depends so little on the memory that hardly more than one reading of the instructions is necessary to obtain a working understanding of the system.

The symbols are of the picture writing form; that is, they show graphically the type of weld required. The joint is the basis of reference and it is said to have an *arrow side*, or *near side*, and an *other side*, or *far side*. The term *both sides* is also used. Of course, all the above expressions are used to locate the weld in reference to the joint. The fundamental kinds of joint, with the line of joint indicated thereon, are shown in Fig. 314.

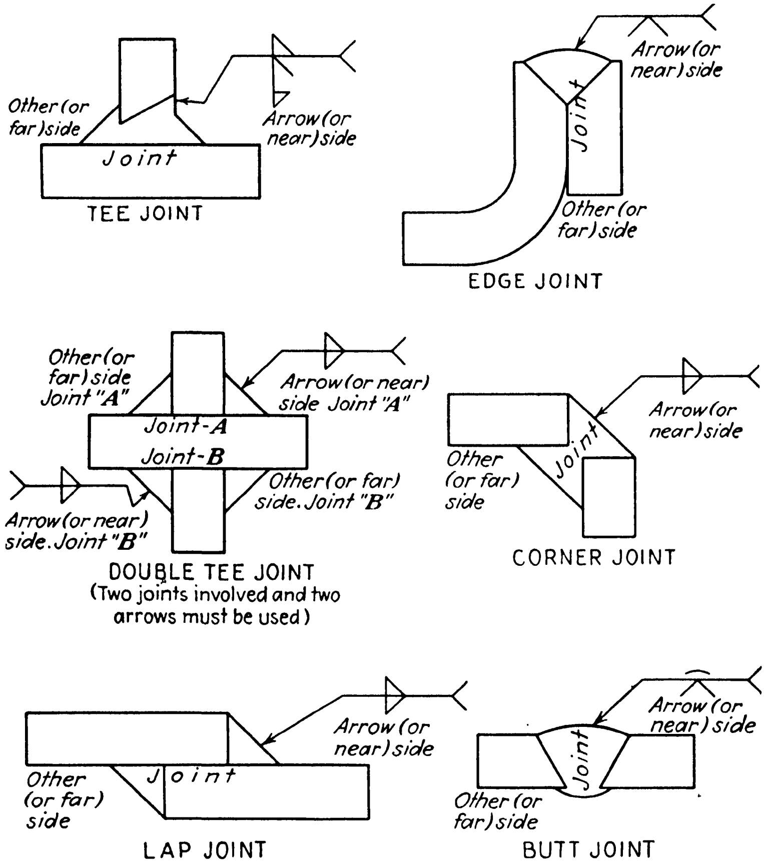


FIG. 314.—Location of line of joint in the various fundamental types of joints.

The additional necessity of appropriate finish marks has been felt, but to date the American Standards Association (A.S.A.) has not decided upon any. However, certain recommendations have been made. It will be noted in Sec. IV of the Instructions that these finish marks merely suggest the means of finishing, that is, whether chipping, grinding, or machining be used, and not the degree. In other words, they do not say whether a weld is to be rough- or finish-machined, rough- or smooth-ground, etc.

The location of numerical data on symbols always has a definite significance. This is illustrated in Fig. 315, where the standard manner of placing information on the symbols is shown diagrammatically. It should be noticed that the perpendicular leg of the weld is always drawn to the left.

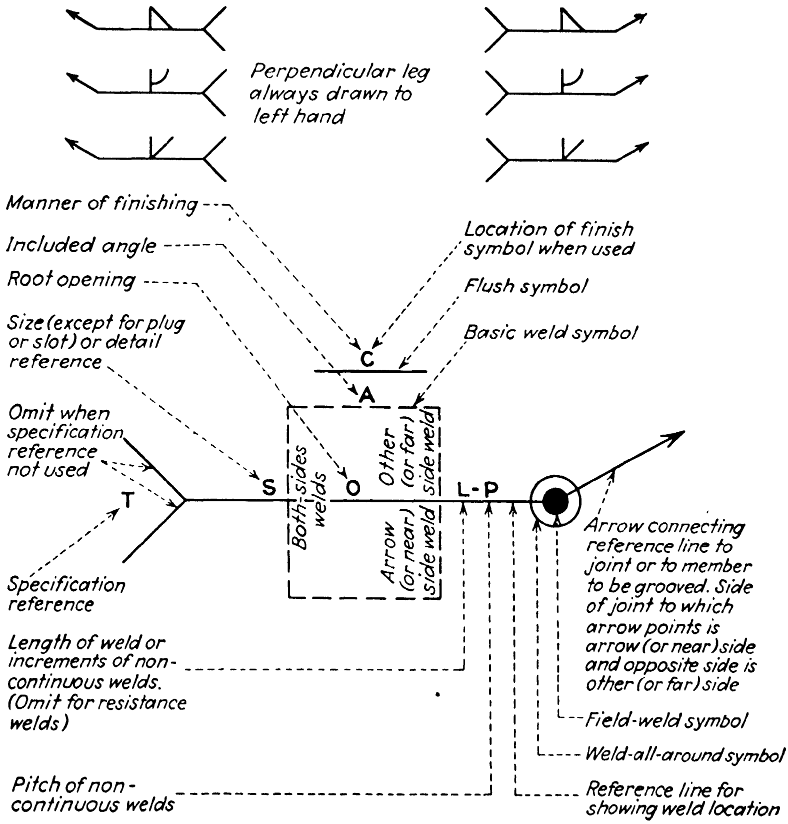

Perpendicular leg always drawn to left hand
Manner of finishing
Included angle
Root opening
Size (except for plug or slot) or detail reference
Omit when specification reference not used
T
Specification reference
Location of finish symbol when used
Flush symbol
Basic weld symbol
C
A
S
O
L-P
Both-sides welds
Other (or far) side weld
Arrow (or near) side weld
Arrow connecting reference line to joint or to member to be grooved. Side of joint to which arrow points is arrow (or near) side and opposite side is other (or far) side
Length of weld or increments of non-continuous welds. (Omit for resistance welds)
Field-weld symbol
Weld-all-around symbol
Pitch of non-continuous welds
Reference line for showing weld location

FIG. 315.—Standard location of information on welding symbols.

Figure 316 shows the proper and improper use of arrows to designate the member to be grooved.

The tail of the arrow is used for referring to the welding specifications to be used in the making of the individual weld. The operator may thus be informed as to the process to be used, type and make of filler rod, whether or not peening or chipping is required, and other pertinent data that he must know before he can start to work.

The symbols constitute a special shorthand system whereby much information may be accurately indicated with a few lines. This is shown in Fig. 317, where the words necessary to convey the information given by the symbol would make a very long paragraph.

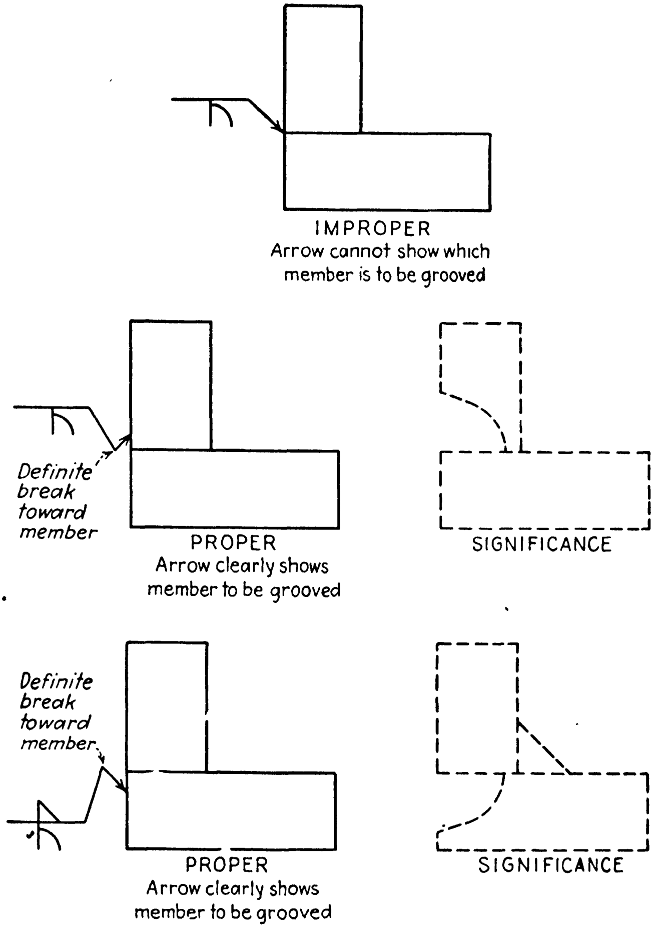
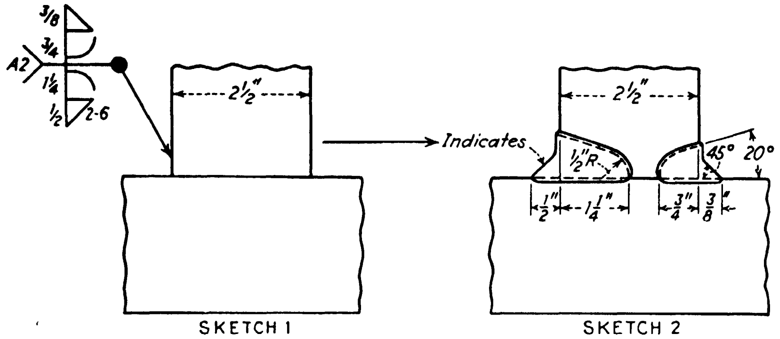

IMPROPER
Arrow cannot show which member is to be grooved
Definite break toward member
PROPER
Arrow clearly shows member to be grooved
SIGNIFICANCE
Definite break toward member
PROPER
Arrow clearly shows member to be grooved
SIGNIFICANCE

FIG. 316.—Use of arrows in section or end view to indicate which member is to be grooved, when welds are not shown.

An illustrative example of how symbols are used on an actual drawing is shown in Fig. 319.

The resistance-welding symbols are similar to those for fusion welding, but there are three principal differences: (1) The resistance symbols are only partly ideographic. (2) The resistance-welding symbols show the strength of the weld but not the size as in the case of fusion-welding symbols. (3) The resistance-welding symbols have no "arrow (near) side" or "other (far) side" significance, except in projection welding, where "arrow" and "other side" refer to the member to be embossed (see Fig. 318).

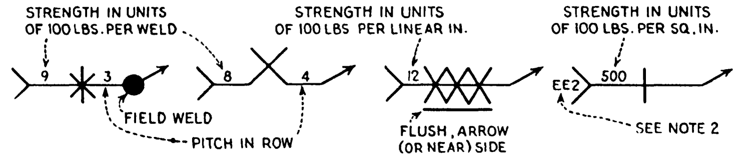


Interpretation of symbol:

Double-fillet-welded, partially-grooved, double-J, tee-joint with incomplete penetration. (Type of joint shown by drawing.) Grooves of standard proportions (which may be ½ in. R. 20° included angle, root edges in contact before welding) ¾ in. deep on far side and 1¼ in. deep on near side; ⅜ in. continuous fillet weld on far side and ½ in. intermittent fillet weld on near side with increments 2 in. long, spaced 6 in. center-to-center. All fillets standard 45° fillets. All welding done in field in accordance with welding specification number A2 (which may require, for example, that weld be made by manual D.C. shielded metal-arc process using high-grade, covered, mild steel electrode; that root be unchipped and welds unpeened but that joint be preheated before welding).

FIG. 317.—Comparison between symbolic and verbal methods of conveying welding information.

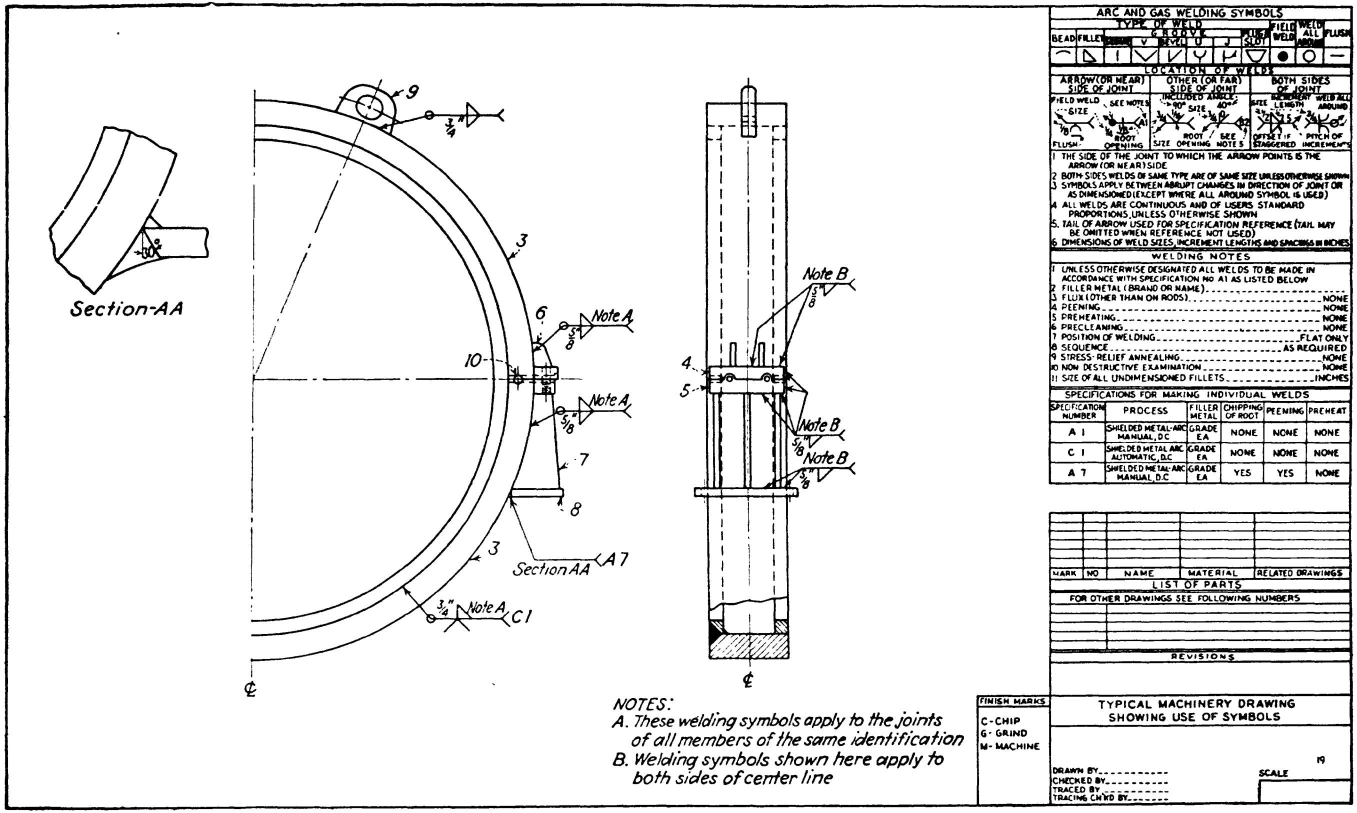
RESISTANCE WELDING SYMBOLS						
TYPE OF WELD				FIELD WELD	WELD ALL AROUND	FLUSH
SPOT	PROJECTION	SEAM	BUTT			
✳	╳	XXX	|	●	○	—


STRENGTH IN UNITS OF 100 LBS. PER WELD
9
3
FIELD WELD
PITCH IN ROW
STRENGTH IN UNITS OF 100 LBS PER LINEAR IN.
8
4
12
FLUSH, ARROW (OR NEAR) SIDE
STRENGTH IN UNITS OF 100 LBS. PER SQ. IN.
EE2
500
SEE NOTE 2

1. SYMBOLS APPLY BETWEEN ABRUPT CHANGES IN DIRECTION OF JOINT OR AS DIMENSIONED (EXCEPT WHERE ALL AROUND SYMBOL IS USED)
2. TAIL OF ARROW USED FOR SPECIFICATION REFERENCE (TAIL MAY BE OMITTED WHEN REFERENCE NOT USED)
3. ALL SPACINGS IN INCHES

FIG. 318.—Legend for use on drawings specifying resistance welding.

One more point to be stressed is that the individual company may use just as much or just as little of the system as it sees fit.



1 THE SIDE OF THE JOINT TO WHICH THE ARROW POINTS IS THE ARROW (OR NEAR) SIDE
2 BOTH-SIDES WELDS OF SAME TYPE ARE OF SAME SIZE UNLESS OTHERWISE SHOWN
3 SYMBOLS APPLY BETWEEN ABRUPT CHANGES IN DIRECTION OF JOINT OR AS DIMENSIONED (EXCEPT WHERE ALL AROUND SYMBOL IS USED)
4 ALL WELDS ARE CONTINUOUS AND OF USERS STANDARD PROPORTIONS, UNLESS OTHERWISE SHOWN
5. TAIL OF ARROW USED FOR SPECIFICATION REFERENCE (TAIL MAY BE OMITTED WHEN REFERENCE NOT USED)
6 DIMENSIONS OF WELD SIZES, INCREMENT LENGTHS AND SPACINGS IN INCHES

WELDING NOTES

1 UNLESS OTHERWISE DESIGNATED ALL WELDS TO BE MADE IN ACCORDANCE WITH SPECIFICATION NO A1 AS LISTED BELOW
2 FILLER METAL (BRAND OR NAME)........................
3 FLUX (OTHER THAN ON RODS)........................NONE
4 PEENING........................NONE
5 PREHEATING........................NONE
6 PRECLEANING........................NONE
7 POSITION OF WELDING........................FLAT ONLY
8 SEQUENCE........................AS REQUIRED
9 STRESS-RELIEF ANNEALING........................NONE
10 NON DESTRUCTIVE EXAMINATION........................NONE
11 SIZE OF ALL UNDIMENSIONED FILLETS........................INCHES

SPECIFICATIONS FOR MAKING INDIVIDUAL WELDS

SPECIFICATION NUMBER	PROCESS	FILLER METAL	CHIPPING OF ROOT	PEENING	PREHEAT
A 1	SHIELDED METAL-ARC MANUAL, DC	GRADE EA	NONE	NONE	NONE
C 1	SHIELDED METAL ARC AUTOMATIC, D.C	GRADE EA	NONE	NONE	NONE
A 7	SHIELDED METAL-ARC MANUAL, D.C	GRADE EA	YES	YES	NONE

NOTES:
A. These welding symbols apply to the joints of all members of the same identification
B. Welding symbols shown here apply to both sides of center line

FIG. 319.—Typical machinery drawing showing use of symbols.

INSTRUCTIONS FOR USE OF WELDING SYMBOLS

I. General.

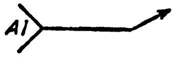
A. Do not use the word "weld" as a symbol on drawings.

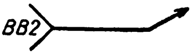
B. Symbols may or may not be made freehand as desired.

C. Inch, degree, and pound marks may or may not be used as desired.

D. The symbol may be used without specification references or tails to designate the most commonly used specification when the following note appears on the drawing:
"Unless otherwise designated, all welds to be made in accordance with welding specification No.________."

E. When specification references are used, place in tail, thus:





F. Symbols apply between abrupt changes in direction of joint or to extent of hatching or dimension lines (except where all-around symbol is used) (see IV *D* and *E*).

G. Faces of welds assumed to have user's standard contours unless otherwise indicated.

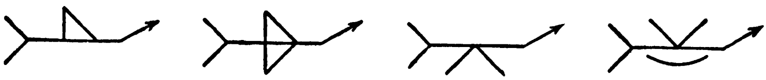
H. Faces of welds assumed not to be finished other than cleaned unless otherwise indicated.

I. All except plug, spot, and projection welds assumed continuous unless otherwise indicated.

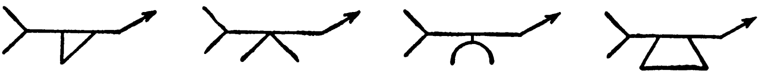
II. Arc and Gas Welds.

A. General.

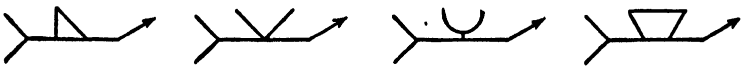
1. Do not put symbol directly on lines of drawing: place symbol on reference line and connect latter to joint with arrow, thus:



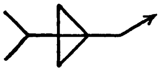
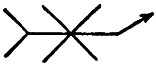
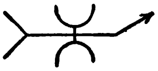
2. For welds on arrow (near) side of joint, show symbol on near side of reference lines, face toward reader, thus:



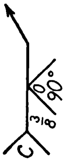
3. For welds on other (far) side, show symbol on far side of reference line, face away from reader, thus:

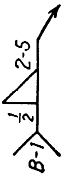


4. For welds on both side of joint, show symbols on both sides of reference line, faces toward and away from reader, thus:

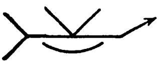
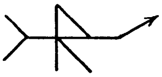
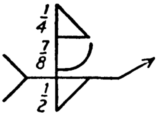




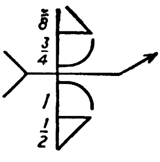
5. Where the part shown is but one of a series of practically identical parts (see the vertical ribs in Fig. 319), the applicability of the symbols to the concealed parts shall be in accordance with the user's standard drawing practices with regard to dimensioning and part-numbering such parts.
6. Where one member only is to be grooved, show arrow pointing unmistakably to that member (see Fig. 316).
7. Read symbols from bottom and right-hand side of drawing in the usual manner, and place numerical data on vertical reference lines so that reader will be properly oriented, thus:





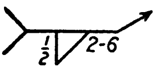
8. Show symbol for each weld in joints composed of more than one weld, thus:

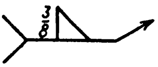




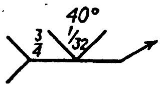


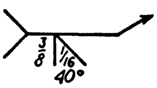
(Give numerical data in proper location with regard to each symbol.)

9. In complicated joints requiring large compound symbols, two separate sets of symbols may be used if desired.
10. Show dimensions of weld on same side of reference line as symbol, thus:



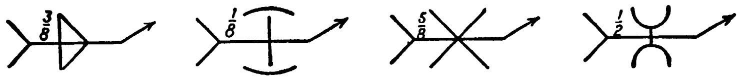




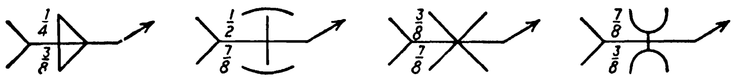


11. Show dimensions of one weld only when welds on both sides of the joint are of the same type and size, thus (if

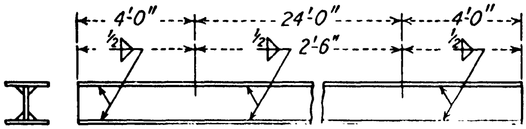
size of undimensioned fillets is governed by a note on the drawing, all weld sizes different from that covered in the note must be given).

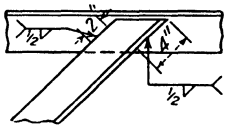


12. Show dimensions for welds on both sides of the joint, when the arrow-side and other-side welds are different, thus:

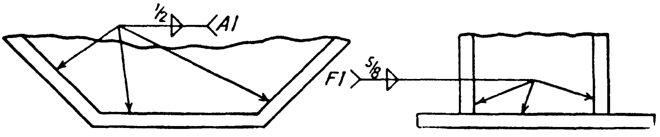


13. Indicate specific lengths of welds in conjunction with dimension lines, thus:

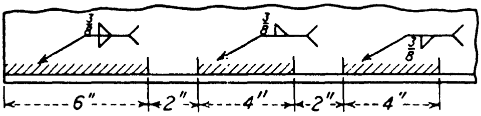


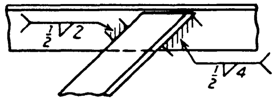


14. Show the welding between abrupt changes in the direction of the weld thus (except when all-around symbol is used; see IV, *D* and *E*):

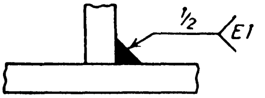


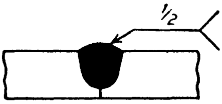
15. When it is desired to show extent of welds by hatching, use one type of hatching with definite end lines, thus:



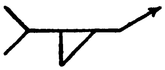


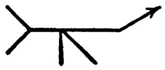
16. If actual outlines of welds are drawn in section or end elevation, basic symbol is not necessary to show type and location; size or other numerical details only need to be given, thus:

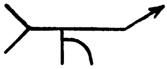




17. Show fillet, bevel- and J-groove weld symbols with perpendicular leg always to the left hand, thus:

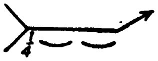


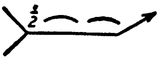


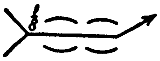


B. Bead Welds.

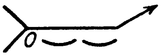
1. Show bead welds used in building up surfaces (size is minimum height of pad), thus:

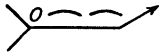


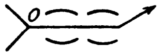




2. When a small but no specific minimum height of pad is desired, show thus:

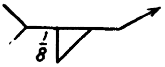


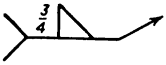


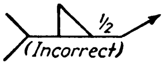


C. Fillet Welds.

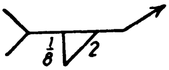
1. Show size of fillet weld to the left of the perpendicular leg, thus:

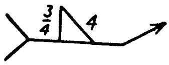




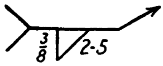


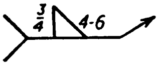
2. Show specific length of fillet weld or increment after size so that data read from left to right, thus:





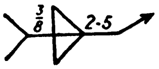
3. Show center-to-center pitch of increments of intermittent fillet welds after increment length so that data read from left to right, thus:



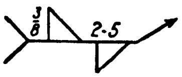


4. Use separate symbol for each weld when intermittent and continuous fillet welds are used in combination.

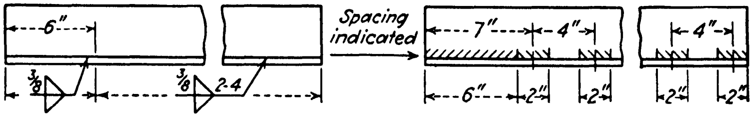
5. Show two intermittent fillet welds with increments opposite each other (chain), thus:



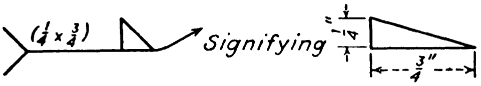
6. Show two intermittent fillet welds with increments not opposite each other (staggered), thus:



7. Measure pitch of intermittent fillet welds between centers of increments on one side of member.
8. Increments and not spaces assumed to be at ends of all intermittent welds, and over-all length dimensions govern to ends of those increments, thus:

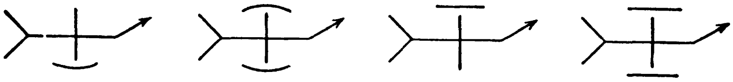


9. Faces of fillet welds assumed to be at 45 deg. from legs unless otherwise indicated.
10. When the face of a fillet weld is to be at any other angle than 45 deg., two dimensions are necessary fully to designate the size of the weld. Place these dimensions in parentheses so that the two-dimensional size data will be a single entity and will not be confused with length-of-increment and spacing data. Show on drawings positions of legs relative to members.

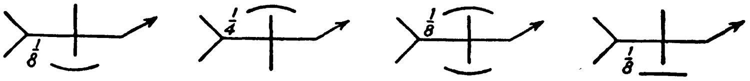


D. Groove Welds.

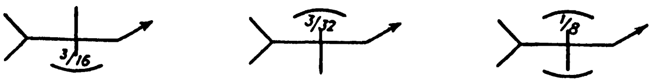
1. Show side from which square-groove weld is made by bead or flush symbols, thus (see III, *D*-1; IV, *H*; and IV, *J* and *K*):



2. Total penetration of square-groove welds assumed to be complete unless otherwise indicated.
3. Show size of square-groove welds (depth of penetration) when penetration is less than complete, thus:

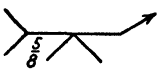


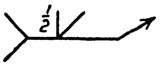
4. Show root opening of open, square-groove welds inside symbol, thus:

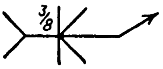


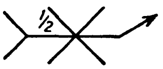
5. Total depth of Vee- and bevel-grooves before welding assumed to be equal to thickness of member unless otherwise indicated

6. Show size of Vee- and bevel-groove welds (depth of single groove before welding) when grooving is less than complete, thus:

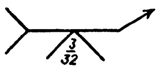


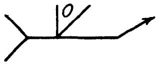


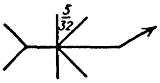


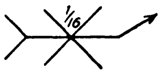


7. Total depth of penetration of Vee- and bevel-groove welds assumed complete, unless, with usual welding processes, depth of grooving is such that complete penetration is not possible, when depth of penetration is assumed to be depth of groove plus normal penetration. In using welding processes giving abnormal penetration, give information on latter by detail or note (see IV, *O*).
8. Root opening of Vee- and bevel-groove welds assumed to be user's standard unless otherwise indicated.
9. Show root openings of Vee- and bevel-groove welds when not user's standard, inside symbol, thus:

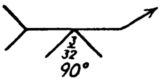


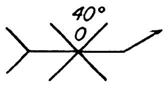


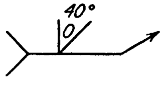


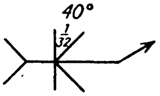


10. Included angle of Vee- and bevel-groove welds assumed to be user's standard unless otherwise indicated.
11. Show included angle of Vee- and bevel-groove welds when not user's standard inside symbol, thus:

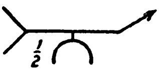


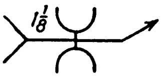


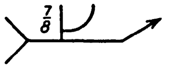


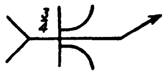


12. Proportions of U- and J-groove welds assumed to be user's standard unless otherwise indicated.
13. Show size of U- and J-groove welds (depth of single groove before welding) having user's standard proportions but incomplete penetration, thus:

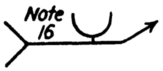


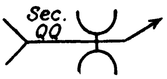


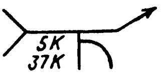


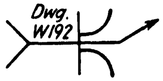


14. When proportions of U- and J-groove welds are not user's standard, show weld by detail or reference drawing and use reference symbol, thus (see IV, *O*):

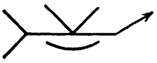
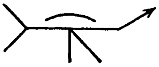
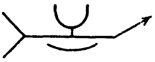
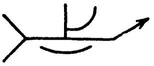






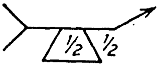


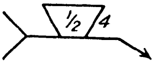
15. Show welding done from root side of single-groove welds with bead weld symbol, thus:

E. Plug and Slot Welds.

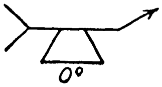
1. Show size of plug and slot welds (root opening and root length), thus:

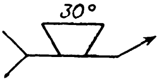




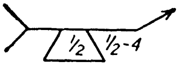
(Root opening equals root length for plug welds.)

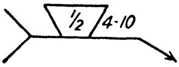
2. Included angle of bevel of plug and slot welds assumed to be user's standard unless otherwise indicated.
3. Show included angle of bevel of plug and slot welds when not user's standard, thus:





4. Show pitch of plug and slot welds in row, thus:



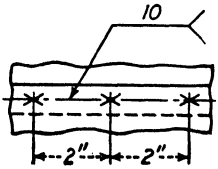


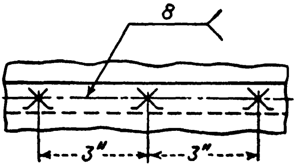
5. Show fillet-welded holes and slots with proper fillet-weld symbols and not with plug-weld symbols.

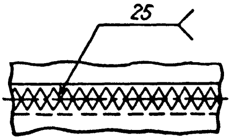
III. Resistance Welds.

A. General.

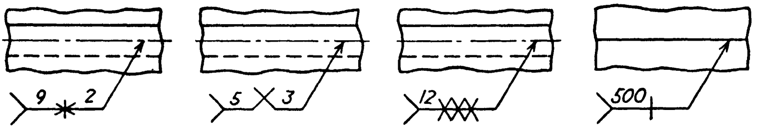
1. Center resistance-welding symbols for spot and seam welds on reference line, for these symbols have no arrow side or other side (near or far side) significance (see Fig. 318 and IV, *M*); but do not center projection-welding symbols, for the latter have such significance.
2. Designate resistance welds by strength rather than size (because of impracticability of determining latter).
3. Spot- and seam-weld symbols may be used directly on drawings, thus (but projection weld symbols should not):



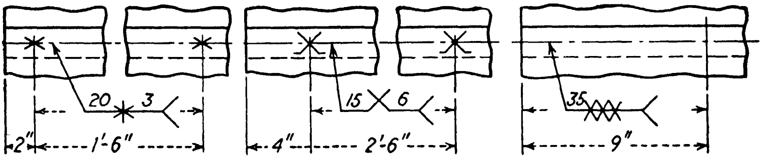




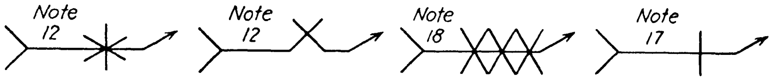
4. When not used on lines of drawing, connect reference line to center line of weld or rows of welds with arrow, thus:



5. Show welds of extent less than between abrupt changes in direction of joint, thus:

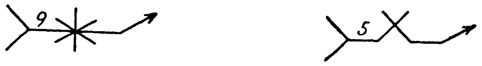


6. When tension, impact, fatigue, or other properties are required, use reference symbol, thus (see IV, *O*):

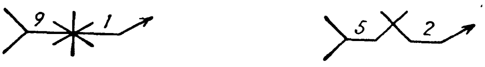


B. Spot and Projection Welds.

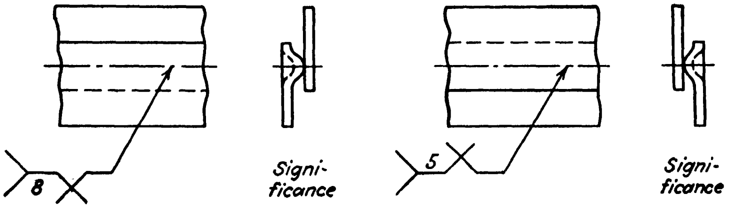
1. Show strength of spot and projection welds in single shear in units of 100 lb. per weld, thus:



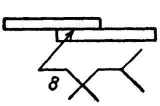
2. Show strength and center-to-center spacing of spot and projection welds in row, thus:

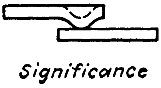


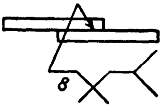
3. Proportions of projections assumed given on drawing.
4. In a projection-welded joint parallel, or nearly so, to the plane of the paper, show whether the arrow (near) side or other (far) side member is to be embossed by placing the projection-weld symbol on the arrow (near) or other (far) side of the reference line, thus:

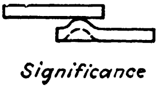


5. In a projection-welded joint shown in section or end view, show which member is to be embossed by pointing arrow to that member, thus:



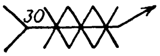






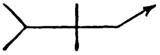
C. Seam Welds.

1. Seam welds assumed to be of overlapping or tangent spots. If any spacing exists between spots, welds considered a series of spot welds, and spot symbol should be used.
2. Show shear strength of seam welds in units of 100 lb. per lin. in., thus:

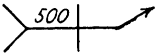


D. Butt Welds.

1. Show resistance butt welds without bead-weld symbol signifying that weld is not made from any side, but all at once, thus (see II, *D*-1):

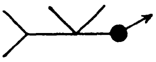


2. Resistance butt welds assumed to be equal to strength of base metal in tension unless otherwise indicated.
3. When a different strength is desired, show strength of butt welds in tension in units of 100 lb. per sq. in., thus:

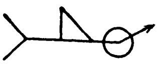


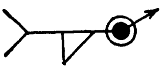
IV. Supplementary Symbols.

A. Show "field" welds (any weld not made in shop), thus:

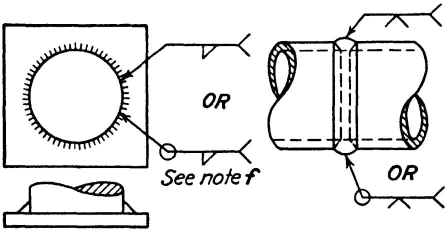


B. Show "all-around" welds, weld encircling joint (or joints) in so far as is possible, thus:

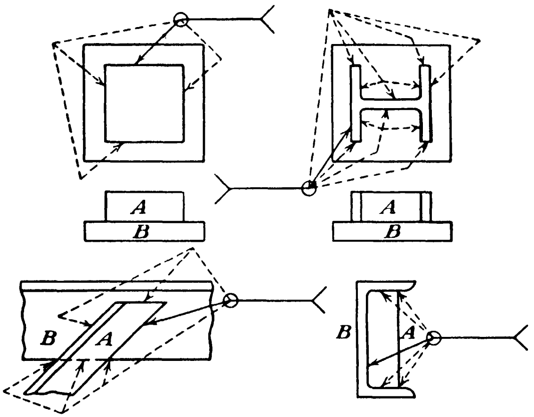




C. When the weld encircles the joint but there is no abrupt change in the direction of the joint or parts of the joint (changes in the direction of rolled structural sections are considered abrupt even though there are fillets in the corners), the all-around symbol may or may not be used as desired, thus:

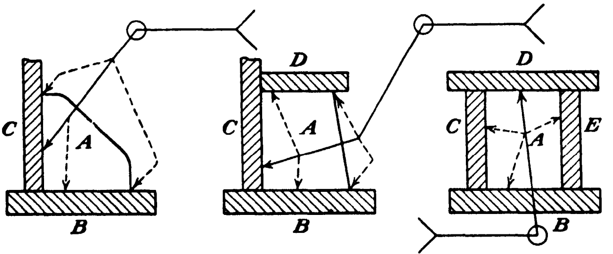


D. The all-around symbol extends control of the welding symbol beyond abrupt changes in the direction of one joint, or parts of one joint, to encirclement of the complete joint in so far as is possible, thus:



One joint between two members "A" and "B"

E. The all-around symbol extends the control of the welding symbol not only beyond abrupt changes in the direction of one joint, but to two or more joints to the encirclement of the joints in so far as is possible, thus:

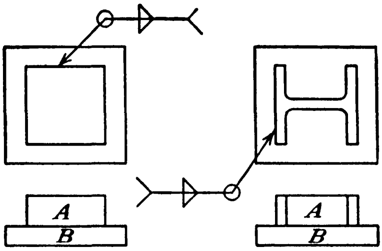


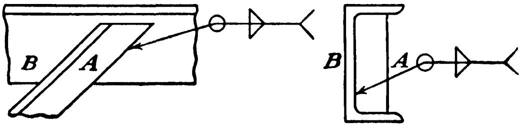
Two joints AB, and AC between 3 members A, B and C

Three joints AB, AC, and AD between 4 members A, B, C and D

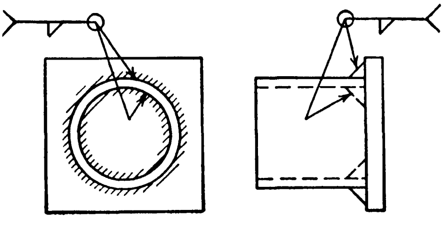
Four joints AB, AC, AD and AE between 5 members A, B, C, D and E

F. When the use of an arrow side or other side symbol, together with an all-around symbol, results in a weld on both sides of the joint as a whole, it is advisable to use the both sides symbol, thus, even though a one side symbol may be strictly correct (see *G* below):





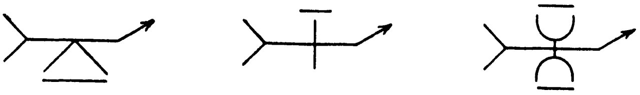
G. When the member involved is hollow or annular and there is more than one encircling weld and there also is likelihood of confusion existing as to whether or not a both sides symbol would refer to a part of the joint or to the joint as a whole, show each encircling weld with a separate arrow, thus:



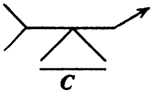
H. The location of the flush and finish symbols have the usual arrow and other (near and far) side significance and govern only the sides on which they are shown.

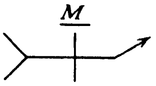
I. Finish marks govern faces of welds only and not base metal either before or after welding.

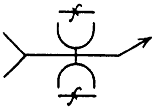
J. Show arc and gas welds made flush without recourse to any kind of finishing, thus:



K. Show arc and gas welds made flush by mechanical means with both flush and user's standard finish symbols, thus:



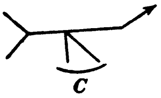


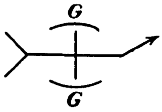


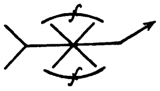
The following letters are suggested for indicating finishing processes:

C—Chip G—Grind M—Machine

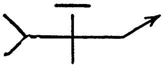
L. Show finishing on face of arc and gas welds, which need not be flush, with user's standard finish symbols on bead symbol, thus:

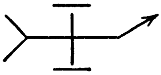


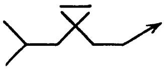


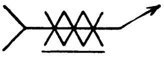


M. Show spot, seam, or projection welds made practically flush (with minimum indentation), thus:

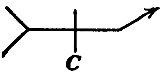


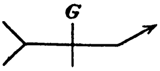


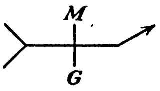




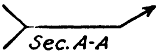
N. Show resistance butt welds, finished by mechanical means, without flush symbol, thus:

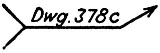


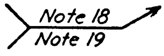




O. Show special welds not covered by any of the above symbols by a detailed section or reference drawing, or give any supplementary information by means of a note and refer weld to section, drawing, or note by a reference symbol. Reference symbol has usual location significance, thus:







APPENDIX

USEFUL ENGINEERING DATA AND TABLES

WEIGHTS AND MEASURES

U.S. System

Length

12 inches = 1 foot (ft.)
3 feet = 1 yard (yd.)
5½ yards or 16½ feet = 1 rod (rd.)
40 rods = 1 furlong (fur.)
8 furlongs = 1 mile (statute) (mi.)

Area

144 square inches = 1 square foot (sq. ft.)
9 square feet = 1 square yard (sq. yd.)
30¼ square yards = 1 square rod (sq. rd.)
40 square rods = 1 rood
4 roods = 1 acre (A.)
640 acres = 1 square mile (sq. mi.)

Volume of Capacity

1,728 cubic inches = 1 cubic foot (cu. ft.)
27 cubic feet = 1 cubic yard (cu. yd.)
128 cubic feet = 1 cord of wood (cd.)
24¾ cubic feet = 1 perch of stone (pch.)

Dry Measure

2 pints = 1 quart (qt.)
8 quarts = 1 peck (pk.)
4 pecks = 1 bushel (2,150.42 cu. in.) (bu.)

Liquid Measure

4 gills = 1 pint (pt.)
2 pints = 1 quart (qt.)
4 quarts = 1 gallon (231 cu. in.)* (gal.)
31½ gal. = 1 barrel (bbl.)
2 barrels = 1 hogshead (hhd.)

Mass (weight) Avoirdupois

16 ounces = 1 pound (7,000 grains) (lb.)
100 pounds = 1 hundredweight (cwt.)
20 hundredweight = 1 ton (T.)

***British imperial gallon = 277.274 cu. in.**

Long Ton

16 ounces = 1 pound (lb.)
28 pounds = 1 quarter (qr.)
4 quarters = 1 hundredweight (cwt.)
20 hundredweight or 2,240 pounds = 1 long ton (T.)

Metric System

Length

10 millimeters (mm.) = 1 centimeter (cm.)
10 centimeters = 1 decimeter (dm.)
10 decimeters = 1 meter (m.)
10 meters = 1 dekameter (dkm.)
10 dekameters = 1 hectometer (hm.)
10 hectometers = 1 kilometer (km.)

Area

100 square millimeters (mm.^{2}) = 1 square centimeter (cm.^{2})
100 square centimeters = 1 square decimeter (dm.^{2})
100 square decimeters = 1 square meter or centare (m.^{2})
100 square meters or centares = 1 are (a.)
100 ares = 1 hectare (ha.)
100 hectares = 1 square kilometer (km.^{2})

Volume of Capacity

1,000 cubic millimeters = 1 cubic centimeter (cm.^{3})
1,000 cubic centimeters = 1 cubic decimeter or 1 liter (dm.^{3})
1,000 cubic decimeters = 1 cubic meter (m.^{3})
1,000 cubic meters = 1 cubic dekameter (dkm.^{3})
1,000 cubic dekameters = 1 cubic hectometer (hm.^{3})
1,000 cubic hectometers = 1 cubic kilometer (km.^{3})

Note: As the above table is too large and unwieldy for ordinary purposes, the following is commonly used:

10 milliliters = 1 centiliter (cl.)
10 centiliters = 1 deciliter (dl.)
10 deciliters = 1 liter or 1 cu. decimeter (l.)
10 liters = 1 dekaliter (dkl.)
10 dekaliters = 1 hectoliter (hl.)
10 hectoliters = 1 kiloliter (kl.)

Mass (weight)

10 milligrams (mg.) = 1 centigram (cg.)
10 centigrams = 1 decigram (dg.)
10 decigrams = 1 gram (g.)
10 grams = 1 dekagram (dkg.)
10 dekagrams = 1 hectogram (hg.)
10 hectograms = 1 kilogram (kg.)
1,000 kilograms = 1 metric ton (t.)

1 cubic centimeter of water at its greatest density (39.2°F. = 4°C.) = 1 gram
1 liter of water = 1 kilogram
International carat = 200 milligrams

METRIC AND ENGLISH CONVERSION TABLES

Linear Measure

1 kilometer = 0.6214 mile
1 meter = 39.37 inches
3.2808 feet
1.0936 yards
1 centimeter = 0.3937 inch
1 millimeter = 0.03937 inch

1 mile = 1.609 kilometers
1 yard = 0.9144 meter
1 foot = 0.3048 meter
1 foot = 304.8 millimeters
1 inch = 2.54 centimeters
1 inch = 25.4 millimeters

Square Measure

1 square kilometer = 0.3861 square mile = 247.1 acres
1 hectare = 2.471 acres = 107,640 square feet
1 are = 0.0247 ares = 1,076.4 square feet
1 square meter = 10.764 square feet = 1.196 square yard
1 square centimeter = 0.155 square inch
1 square millimeter = 0.00155 square inch.

1 square mile = 2.5899 square kilometers
1 acre = 0.4047 hectare = 40.47 ares
1 square yard = 0.836 square meter
1 square foot = 0.0929 square meter = 9,290 square centimeters
1 square inch = 6.452 square centimeters = 645.2 square millimeters

Cubic Measure

1 cubic meter = 35.314 cubic feet = 1.308 cubic yard
1 cubic meter = 264.2 U.S. gallons
1 cubic centimeter = 0.061 cubic inch
1 liter (cubic decimeter) = 0.0353 cubic foot = 61.023 cubic inches
1 liter = 0.2642 U.S. gallon = 1.0567 U.S. quarts

1 cubic yard = 0.7645 cubic meter
1 cubic foot = 0.02832 cubic meter = 28.317 liters
1 cubic inch = 16.383 cubic centimeters
1 U.S. gallon = 3.785 liters
1 U.S. quart = 0.946 liter

Weight

1 metric ton = 1.1025 ton = 2,204.6 pounds
1 kilogram = 2.2046 pounds = 35.274 ounces avoirdupois
1 gram = 0.03216 ounce troy = 0.03527 ounce avoirdupois
1 gram = 15.432 grains

1 ton (of 2,000 pounds) = 0.9842 metric ton = 907.18 kilograms
1 pound = 0.4536 kilogram = 453.6 grams
1 ounce avoirdupois = 28.35 grams
1 ounce troy = 31.103 grams
1 grain = 0.0648 gram

1 kilogram per square millimeter = 1,422.32 pounds per square inch
1 kilogram per square centimeter = 14.223 pounds per square inch

1 kilogram-meter = 7.233 foot-pounds

1 pound per square inch = 0.0703 kilogram per square centimeter

1 calorie (metric thermal unit) = 3.968 B.t.u. (British thermal unit)

Metric Conversion Factors

Inches to centimeters—1 in. = 2.540005 cm.

Inches^2 to centimeters^2—1 in.^{2} = 6.451625 cm.^{2}

Inches^3 to centimeters^3—1 in.^{3} = 16.38716 cm.^{3}

Inches^4 to centimeters^4—1 in.^{4} = 41.62347 cm.^{4}

Centimeters to inches—1 cm. = 0.3937 in.

Centimeters^2 to inches^2—1 cm.^{2} = 0.15499969 in.^{2}

Centimeters^3 to inches^3—1 cm.^{3} = 0.0610234 in.^{3}

Centimeters^4 to inches^4—1 cm.^{4} = 0.0240249 in.^{4}

Feet to meters—1 ft. = 0.3048006 m.

Pounds per foot to kilograms per meter—1 lb. per ft. = 1.488161 kg. per m.

Pounds per square inch to kilograms per square centimeter—1 lb. per in.^{2} = 0.0703067 kg. per cm.^{2}

Inch-pounds to kilogram-centimeters—1 in.-lb. = 1.152127 kg.-cm.

Meters to feet—1 m. = 3.2808333 ft.

Kilograms per meter to pounds per foot—1 kg. per m. = 0.67197 lb. per ft.

Kgs. per square centimeter to pounds per square inch—1 kg. per cm.^{2} = 14.2234 lbs. per in.^{2}

Kilogram-centimeters to inch-pounds—1 kg.-cm. = 0.86796 in.-lb.

METRIC AND DECIMAL EQUIVALENTS OF COMMON FRACTIONS*

Fractions, in.	Decimals, in.	Mm.	Fractions, in.	Decimals, in.	Mm.
1/64	0.0156	0.397	33/64	0.5156	13.097
1/32	0.0313	0.794	17/32	0.5313	13.494
3/64	0.0469	1.191	35/64	0.5469	13.891
1/16	0.0625	1.588	9/16	0.5625	14.288
5/64	0.0781	1.985	37/64	0.5781	14.684
3/32	0.0938	2.381	19/32	0.5938	15.081
7/64	0.1094	2.778	39/64	0.6094	15.478
1/8	0.1250	3.175	5/8	0.6250	15.875
9/64	0.1406	3.572	41/64	0.6406	16.272
5/32	0.1563	3.969	21/32	0.6563	16.669
11/64	0.1719	4.366	43/64	0.6719	17.066
3/16	0.1875	4.763	11/16	0.6875	17.463
13/64	0.2031	5.159	45/64	0.7031	17.859
7/32	0.2188	5.556	23/32	0.7188	18.256
15/64	0.2344	5.953	47/64	0.7344	18.653
1/4	0.2500	6.350	3/4	0.7500	19.050
17/64	0.2656	6.747	49/64	0.7656	19.447
9/32	0.2813	7.144	25/32	0.7813	19.844
19/64	0.2969	7.541	51/64	0.7969	20.241
5/16	0.3125	7.938	13/16	0.8125	20.638
21/64	0.3281	8.334	53/64	0.8281	21.034
11/32	0.3438	8.731	27/32	0.8438	21.431
23/64	0.3594	9.128	55/64	0.8594	21.828
3/8	0.3750	9.525	7/8	0.8750	22.225
25/64	0.3906	9.922	57/64	0.8906	22.622
13/32	0.4063	10.319	29/32	0.9063	23.019
27/64	0.4219	10.716	59/64	0.9219	23.416
7/16	0.4375	11.113	15/16	0.9375	23.813
29/64	0.4531	11.509	61/64	0.9531	24.209
15/32	0.4688	11.906	31/32	0.9688	24.606
31/64	0.4844	12.303	63/64	0.9844	25.003
1/2	0.5000	12.700		1.0000	25.400

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* **SOURCE:** U.S. Bureau of Standards.

WIRE AND SHEET-METAL GAUGES

Number of gauge	Birmingham (or Stubs) iron-wire gauge, in.	American or Brown and Sharpe copper-wire gauge, in.	Roebling's and Washburn and Moen's steel-wire gauge, in.	Stubs steel-wire gauge, in.	British imperial standard wire gauge, 1,884 in.	British standard B.G. gauge, 1914, for iron and steel sheets and hoops, in.	U.S. standard gauge for sheet and plate iron and steel, 1893, in.	Number of gauge
0000000	.....	....	0.49	.....	0.500	0.6666	0.5	7/0
000000	.....	....	0.46	.....	0.464	0.625	0.469	6/0
00000	.....	....	0.43	.....	0.432	0.5883	0.438	5/0
0000	0.454	0.46	0.393	.....	0.4	0.5416	0.406	4/0
000	0.425	0.40964	0.362	.....	0.372	0.500	0.375	3/0
00	0.38	0.3648	0.331	.....	0.348	0.4452	0.344	2/0
0	0.34	0.32486	0.307	.....	0.324	0.3964	0.313	0
1	0.3	0.2893	0.283	0.227	0.3	0.3532	0.281	1
2	0.284	0.25763	0.263	0.219	0.276	0.3147	0.266	2
3	0.259	0.22942	0.244	0.212	0.252	0.2804	0.25	3
4	0.238	0.20431	0.225	0.207	0.232	0.250	0.234	4
5	0.22	0.18194	0.207	0.204	0.212	0.2225	0.219	5
6	0.203	0.16202	0.192	0.201	0.192	0.1981	0.203	6
7	0.18	0.14428	0.177	0.199	0.176	0.1764	0.188	7
8	0.165	0.12849	0.162	0.197	0.16	0.1570	0.172	8
9	0.148	0.11443	0.148	0.194	0.144	0.1398	0.156	9
10	0.134	0.10189	0.135	0.191	0.128	0.1250	0.141	10
11	0.12	0.09074	0.12	0.188	0.116	0.1113	0.125	11
12	0.109	0.08081	0.105	0.185	0.104	0.991	0.109	12
13	0.095	0.07196	0.092	0.182	0.092	0.0882	0.094	13
14	0.083	0.06408	0.08	0.180	0.08	0.0785	0.078	14
15	0.072	0.05707	0.072	0.178	0.072	0.0699	0.07	15
16	0.065	0.05082	0.063	0.175	0.064	0.0625	0.0625	16
17	0.058	0.04526	0.054	0.172	0.056	0.0556	0.0563	17
18	0.049	0.0403	0.047	0.168	0.048	0.0495	0.05	18
19	0.042	0.03589	0.041	0.164	0.04	0.0440	0.0438	19
20	0.035	0.03196	0.035	0.161	0.036	0.0392	0.0375	20
21	0.032	0.02846	0.032	0.157	0.032	0.0349	0.0344	21
22	0.028	0.02535	0.028	0.155	0.028	0.03125	0.0313	22
23	0.025	0.02257	0.025	0.153	0.024	0.02782	0.0281	23
24	0.022	0.0201	0.023	0.151	0.022	0.02476	0.025	24
25	0.02	0.0179	0.02	0.148	0.02	0.02204	0.0219	25
26	0.018	0.01594	0.018	0.146	0.018	0.01961	0.0188	26
27	0.016	0.01419	0.017	0.143	0.0164	0.01745	0.0172	27
28	0.014	0.01264	0.016	0.139	0.0148	0.015625	0.0156	28
29	0.013	0.01126	0.015	0.134	0.0136	0.0139	0.0141	29
30	0.012	0.01002	0.014	0.127	0.0124	0.0123	0.0125	30

TEMPERATURE CONVERSION TABLE

Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit
-40	-40	13	55.5	56	132.8	99	210.2
-38	-36	14	57.2	57	134.6	100	212.0
-36	-32	15	59.0	58	136.4	101	213.8
-34	-29	16	60.8	59	138.2	102	215.6
-32	-25	17	62.6	60	140.0	103	217.4
-30	-22	18	64.4	61	141.8	104	219.2
-28	-18	19	66.2	62	143.6	105	221.0
-26	-14	20	68.0	63	145.4	106	222.8
-24	-11	21	69.8	64	147.2	107	224.6
-22	- 7	22	71.6	65	149.0	108	226.4
-20	- 4	23	73.4	66	150.8	109	228.2
-19	- 2.2	24	75.2	67	152.6	110	230.0
-18	- 0.4	25	77.0	68	154.4	111	231.8
-17	+ 1.4	26	78.8	69	156.2	112	233.6
-16	3.2	27	80.6	70	158.0	113	235.4
-15	5.0	28	82.4	71	159.8	114	237.2
-14	6.8	29	84.2	72	161.6	115	239 0
-13	8 6	30	86.0	73	163.4	116	240.8
-12	10 4	31	87 8	74	165.2	117	242.6
-11	12.2	32	89.6	75	167.0	118	244.4
-10	14.0	33	91.4	76	168 8	119	246.2
- 9	15.8	34	93.2	77	170.6	120	248.0
- 8	17.6	35	95.0	78	172.4	121	249.8
- 7	19.4	36	96.8	79	174 2	122	251.6
- 6	21.2	37	98.6	80	176.0	123	253.4
- 5	23.0	38	100.4	81	177.8	124	255.2
- 4	24.8	39	102.2	82	179.6	125	257.0
- 3	26.6	40	104.0	83	181.4	126	258.8
- 2	28.4	41	105.8	84	183.2	127	260.6
- 1	30.2	42	107.6	85	185.0	128	262.4
0	32.0	43	109.4	86	186.8	129	264.2
1	33.8	44	111.2	87	188.6	130	266.0
2	35.6	45	113.0	88	190.4	131	267.8
3	37.4	46	114.8	89	192.8	132	269.6
4	39.2	47	116.6	90	194.0	133	271.4
5	41.0	48	118.4	91	195.8	134	273.2
6	42.8	49	120.2	92	197.6	135	275.0
7	44.6	50	122.0	93	199.4	136	276.8
8	46.4	51	123.8	94	201.2	137	278.6
9	48.2	52	125.6	95	203.0	138	280.4
10	50.0	53	127.4	96	204.8	139	282.2
11	51.8	54	129.2	97	206.6	140	284.0
12	53.6	55	131.0	98	208.4	141	285.8

EXPANSION OF HEATED METALS

[Expansion, in., of a bar 1 ft. long when its temperature is raised 100°C. (180°F.)]

Metal	Expansion, In.	Expansion, Mm.
Aluminum	0.0267	0.67818
Cast iron	0.0133	0.33782
Mild steel	0.0144	0.36576
Copper	0.0206	0 52324
Brass (cast)	0.0225	0 57150
Silver	0.0229	0.58166
Wrought iron	0.0148	0.37592
Lead	0.0340	0.8636
Tin	0.0266	0.62564
Zinc	0.0354	0.89916
Stainless iron:		
18 per cent Cr, 8 per cent Ni	0.0210	0.5334
12 per cent Cr	0.0120	0.3048
Monel metal	0 0170	0.4318
Manganese steel	0.0350	0.8890

Weight of Various Metals, Bars, and Plates

Metal	Lb. per Cu. In.
Iron	0.2778
Steel	0.2833
Copper	0.3212
Brass	0.3112
Lead	0.4102
Zinc	0.2532
Tin	0.2656
Aluminum	0.0938

Bar steel (weight per lineal foot):

Find area of one end in square inches, add a cipher, and divide by 3 to get pounds per lineal foot.

Properties of Elements and Metal Compositions

Elements	Symbol	Density (specific gravity)	Weight per cu. ft.	Specific heat	Melting point	
					°C.	°F.
Aluminum	Al	2.7	166.7	0.212	658.7	1217.7
Antimony	Sb	6.69	418.3	0.049	630	1166
Armco iron	..	7.9	490.0	0.115	1535	2795
Carbon	C	2.34	219.1	0.113	3600	6512
Chromium	Cr	6.92	431.9	0.104	1615	3034
Columbium	Cb	7.06	452.54	.....	1700	3124
Copper	Cu	8.89	555.6	0.092	1083	1981.4
Gold	Au	19.33	1205.0	0.032	1063	1946
Hydrogen	H	0.070*	0.00533	.....	− 259	− 434.2
Iridium	Ir	22.42	1400.0	0.032	2300	4172
Iron	Fe	7.865	490.9	0.115	1530	2786
Lead	Pb	11.37	708.5	0.030	327	621
Manganese	Mn	7.4	463.2	0.111	1260	2300
Mercury	Hg	13.55	848.84	0.033	− 38.7	− 37.6
Nickel	Ni	8.80	555.6	0.109	1452	2645.6
Nitrogen	N	0.97*	0.063	.....	− 210	− 346
Oxygen	O	1.10*	0.0866	.....	− 218	− 360
Phosphorus	P	1.83	146.1	0.19	44	111.2
Platinum	Pt	21.45	1336.0	0.032	1755	3191
Potassium	K	0.87	54.3	0.170	62.3	144.1
Silicon	Si	2.49	131.1	0.175	1420	2588
Silver	Ag	10.5	655.5	0.055	960.5	1761
Sodium	Na	0.971	60.6	0.253	97.5	207.5
Sulphur	S	1.95	128.0	0.173	119.2	246
Tin	Sn	7.30	455.7	0.054	231.9	449.5
Titanium	Ti	5.3	218.5	0.110	1795	3263
Tungsten	W	17.5	1186.0	0.034	3000	5432
Uranium	U	18.7	1167.0	0.028		
Vanadium	V	6.0	343.3	0.115	1720	3128
Zinc	Zn	7.19	443.2	0.093	419	786.2
Bronze (90 per cent Cu 10 per cent Sn)	..	8.78	548.0	.....	850–1000	1562–1832
Brass (90 per cent Cu 10 per cent Zn)	..	8.60	540.0	.....	1020–1030	1868–1886
Brass (70 per cent Cu 30 per cent Zn)	..	8.44	527.0	.....	900– 940	1652–1724
Cast pig iron	..	7.1	443.2	.....	1100–1250	2012–2282
Open-hearth steel	..	7.8	486.9	.....	1350–1530	2462–2786
Wrought-iron bars	..	7.8	486.9	.....	1530	2786

* Density compared with air.

ALLOWABLE CARRYING CAPACITIES OF BUILDING-TYPE COPPER WIRE
(Regulations of the National Board of Fire Underwriters)

No. A.W.G.	Cir. mils	Carrying capacity, amp.		Cir. mils	Carrying capacity, amp.	
		Rubber insulation	Varnished-cambric insulation		Rubber insulation	Varnished-cambric insulation
18	1,624	3	4	250,000	250	300
16	2,583	6	8	300,000	275	330
14	4,107	15	18	350,000	300	360
12	6,530	20	25	400,000	325	390
10	10,380	25	30	450,000	362	435
8	16,510	35	40	500,000	400	480
6	26,250	50	60	600,000	450	540
4	41,740	70	85	700,000	500	600
2	66,370	90	110	800,000	550	660
1	83,690	100	120	1,000,000	650	780
0	105,500	125	150	1,250,000	750	900
00	133,100	150	180	1,500,000	850	1020
000	167,800	175	210	1,750,000	950	1140
0000	211,600	225	270	2,000,000	1050	1260

Useful Electrical Formulas for Determining Amperes, Horsepower, Kilowatts, and Kilovolt-amperes

To find	Direct current	Alternating current		
		Single phase	Two phase* four wire	Three phase
Amp. when hp. is known	$\frac{\text{Hp.} \times 746}{V. \times E.}$	$\frac{\text{Hp.} \times 746}{V. \times E. \times \text{P.F.}}$	$\frac{\text{Hp.} \times 746}{2 \times V. \times E. \times \text{P.F.}}$	$\frac{\text{Hp.} \times 746}{173 \times V. \times E. \times \text{P.F.}}$
Amp. when kw. is known	$\frac{\text{Kw.} \times 1{,}000}{V.}$	$\frac{\text{Kw.} \times 1{,}000}{V. \times \text{P.F.}}$	$\frac{\text{Kw.} \times 1{,}000}{2 \times V. \times \text{P.F.}}$	$\frac{\text{Kw.} \times 1{,}000}{173 \times V. \times \text{P.F.}}$
Amp. when kva. is known	....	$\frac{\text{Kva.} \times 1{,}000}{V.}$	$\frac{\text{Kva.} \times 1{,}000}{2 \times V.}$	$\frac{\text{Kva.} \times 1{,}000}{173 \times V.}$
Kw	$\frac{I \times V.}{1{,}000}$	$\frac{I \times V. \times \text{P.F.}}{1{,}000}$	$\frac{I \times V. \times 2 \times \text{P.F.}}{1{,}000}$	$\frac{I \times V. \times 173 \times \text{P.F.}}{1{,}000}$
Kva	....	$\frac{I \times V.}{1{,}000}$	$\frac{I \times V. \times 2}{1{,}000}$	$\frac{I \times V. \times 173}{1{,}000}$
Hp. (output)	$\frac{I \times V. \times E.}{746}$	$\frac{I \times V. \times E. \times \text{P.F.}}{746}$	$\frac{I \times V. \times 2 \times E. \times \text{P.F.}}{746}$	$\frac{I \times V. \times 173 \times E. \times \text{P.F.}}{746}$

I = amperes; $V.$ = volts; $E.$ = per cent efficiency; P.F. = power factor; kw. = kilowatts; kva. = kilovolt-amperes; hp. = per cent horsepower.

* For three-wire two-phase circuits the current in the common conductor is 1.41 times that in either of the two conductors.

DIAMETER, WEIGHT, AND RESISTANCE OF STANDARD ANNEALED COPPER WIRE ROUND SOLID CONDUCTOR

(Based on U.S. Bureau of Standards)

No. A.W.G.	Diameter, mils	Area, cir. mils	Weight bare wire, lb. per 1,000 ft.	Resistance at 25°C. (77°F.)	
				Ohms per 1,000 ft.	Ft. per ohm
0000	460	211,600	640.5	0.04998	20,010
000	410	167,800	507.9	0.06302	15,870
00	365	133,100	402.8	0.07947	12,580
0	325	105,500	319.5	0.1002	9,980
1	289	83,690	253.3	0.1264	7,914
2	258	66,370	200.9	0.1593	6,276
3	229	52,640	159.3	0.2009	4,977
4	204	41,740	126.4	0.2533	3,947
5	182	33,100	100.2	0.3195	3,130
6	162	26,250	79.46	0.4028	2,482
7	144	20,820	63.02	0.5080	1,969
8	128	16,510	49.98	0.6405	1,561
9	114	13,090	39.63	0.8077	1,238
10	102	10,380	31.43	1.018	981.8
11	91	8,234	24.92	1.284	778.7
12	81	6,530	19.77	1.619	617.5
13	72	5,178	15.68	2.042	489.7
14	64	4,107	12.43	2.575	388.3
15	57	3,257	9.858	3.247	308.0
16	51	2,583	7.818	4.094	244.2
17	45	2,048	6.200	5.163	193.7
18	40	1,624	4.917	6.510	153.6
19	36.0	1,288	3.899	8.210	121.8
20	32.0	1,022	3.092	10.35	96.60
21	28.5	810.1	2.452	13.05	76.61
22	25.3	642.4	1.945	16.46	60.75
23	22.6	509.5	1.542	20.76	48.18
24	20.1	404.0	1.223	26.17	38.21
25	17.9	320.4	0.9699	33.00	30.30
26	15.9	254.1	0.7692	41.62	24.03
27	14.2	201.5	0.6100	52.48	19.06
28	12.6	159.8	0.4837	66.17	15.11
29	11.3	126.7	0.3836	83.44	11.98
30	10.0	100.5	0.3042	105.2	9.504
31	8.9	79.70	0.2413	132.7	7.537
32	8.0	63.21	0.1913	167.3	5.977
33	7.1	50.13	0.1517	211.0	4.740
34	6.3	39.75	0.1203	266.0	3.759
35	5.6	31.52	0.09542	335.5	2.981
36	5.0	25.00	0.07568	423.0	2.364
37	4.5	19.83	0.06001	533.4	1.875
38	4.0	15.72	0.04759	672.6	1.487
39	3.5	12.47	0.03774	848.1	1.179
40	3.1	9.89	0.02993	1,069	0.9350
41	2.8	7.84	0.02374	1,349	0.7415
42	2.5	6.22	0.01883	1,701	0.5880
43	2.2	4.93	0.01493	2,144	0.4663
44	2.0	3.91	0.01184	2,704	0.3698

USEFUL INFORMATION

Circle:

Circumference = diameter × 3.1416
Diameter = circumference × 0.3138
Area = (square of diameter) × 0.7854
Doubling the diameter increases the area four times.
Side of an equal square = diameter × 0.8862
Side of an inscribed square = diameter × 0.7071 = circumference × 0.2251
Area of inscribed square = 0.6366 × area of circle

Rectangle:

Area = length × width

Triangle:

Area = base × ½ perpendicular height

Square:

Diameter of circumscribing circle = side × 1.4142
Diameter of equal circle = side × 1.128

Sphere or ball:

Area of surface = (square of diameter) × 3.1416
Volume (cubic inches, feet, etc.) = (cube of diameter) × 0.5236

Cone:

Volume = area of base × ⅓ altitude

Miscellaneous:

Doubling the diameter of a pipe increases its capacity four times.

A gallon of water (U.S. Standard) weighs 8⅓ lb. and contains 231 cu. in.

A cubic foot of water contains 7½ gal., 1,728 cu. in., and weighs 62½ lb.

To find the pressure in pounds per square inch of a column of water, multiply the height of the column in feet by 0.434.

To find the capacity of tanks of any size, given dimensions of a cylinder in inches. to find its capacity in U.S. gallons: square the diameter, and multiply by the length and by 0.0034.

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